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Pig Waste Management and Recycling

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Pig Waste Management and Recycling

The Singapore Experience

E. Paul Taiganides

INTERNATIONAL DEVELOPMENT RESEARCH CENTRE
Ottawa • Cairo • Dakar • Johannesburg • Montevideo • Nairobi • New Delhi • Singapore

Abstract

For the island republic of Singapore, the decade from 1975 to 1985 produced the most phenomenal changes in its history. This textbook-cum-research report chronicles one aspect of that change: the pig-farming industry. It covers everything from biomass recovery to malodour prevention and, while focusing on the Singapore experience, the approaches, conclusions, and technologies described are pertinent to all systems that must deal with organic solid wastes and wastewaters, particularly in the livestock industry of the world's tropical regions. This book is aimed at professional engineers, researchers, policymakers, and, in conjunction with other more basic textbooks, graduate students in waste management and evironmental engineering.

Résumé

Au cours de la décennie allant de 1975 à 1985, la République de Singapour a connu les plus importants changements de toute son histoire. Ce livre, qui est à la fois un manuel didactique et un rapport de recherche, porte sur les changements qui se sont produits dans l'industrie de l'élevage du porc. Il en aborde tous les aspects de façon exhaustive, de la récupération de la biomasse à la prévention des mauvaises odeurs. S'il met l'accent sur l'expérience menée à Singapour, les approches, conclusions et techniques qui y sont décrites peuvent convenir à tous les systèmes où il y a production de déchets organiques solides et d'eaux usées, et tout particulièrement à l'industrie de l'élevage en milieu tropical. Ce livre s'adresse aux ingénieurs, chercheurs et décideurs, et, utilisé avec d'autres manuels plus fondamentaux, aux étudiants de cycle supérieur dans les domaines de la gestion des déchets et du génie de l'environnement.

Resumen

Para la isleña república de Singapur, la década de 1975 a 1985 produjo los cambios más espectaculares en su historia. Este informe combinado investigación-libro de texto, establece la crónica de un aspecto de ese cambio: la industria de la cría del ganado de cerda. Abarca prácticamente todo, desde la recuperación de la biomasa, hasta la prevención de los olores ofensivos y, mientras que el texto se centra en la experiencia de Singapur, los enfoques, las conclusiones y las tecnologías descritas son aplicables a todos los sistemas que tratan con desperdicios, desechos y aguas residuales, especialmente en la industria ganadera de las regiones tropicales del mundo. Este libro se dirige a los ingenieros profesionales, investigadores, responsables de la formulación de políticas y en conjunción con otros textos más básicos, a los estudiantes graduados en la gestión de desperdicios y basuras e ingeniería del medio ambiente.

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Foreword

This book is a compilation of the results of a decade of research and development. The problem was to design and develop universally applicable technologies for wastewater treatment and resource recovery. A special effort was made to develop systems of modular units that could be adapted by farmers over a reasonable period of compliance. The technologies described in this book are a valuable resource for anyone faced with the problem of pollution caused by animal waste.

Although pig farming in Singapore has ceased because of the competing need for land for housing and industry in our land-scarce island republic, the thorough and comprehensive work in the field of waste management and utilization, so ably carried out by Professor Taiganides and his team of scientists, will serve as a landmark and valuable reference for everyone concerned with the preservation of the environment. The information contained in *Pig Waste Management and Recycling* will serve the compelling need for waste management and utilization in the livestock industry worldwide, and particularly in the tropical belts of the world.

Pig Waste Management and Recycling reflects the dedication of the many scientists and engineers who devoted part of their professional life to experimenting with innovative approaches to livestock rearing in an environmentally acceptable manner. This book could not possibly include the details of the work of these researchers, but their expertise can now be tapped by those who are and will be working in livestock development projects.

The Ministry of National Development is indebted to the international agencies that supported this valuable work: the Australian Development Assistance Bureau (ADAB), the Food and Agriculture Organization of the United Nations (FAO), the German Technical Assistance Agency (GTZ), the International Development Research Centre (IDRC) of Canada, the United Nations Development Programme (UNDP), and others that contributed through the Association of South East Asian Nations (ASEAN). We also acknowledge the important contribution made by the livestock farmers who agreed to be trained in modern methods of pig rearing and to adopt environmental control measures. Finally, we are grateful to Professor E. Paul Taiganides for sifting through voluminous research reports and writing this cogent textbook and to IDRC for publishing this work for worldwide distribution.

Dr Ngiam Tong Tau

Director
Primary Production Department
Ministry of National Development
Republic of Singapore

Preface

I arrived in Singapore in December 1975 on a 1-year leave from Ohio State University to manage a United Nations project. I stayed 15 years: 10 years in Singapore, 2 years in Malaysia, and 3 years travel throughout Southeast Asia. It was a period of extraordinary change in Southeast Asia. For me, it was a marvelous experience, the technical components of which are contained in this book.

A Decade of Change

In the 10 years from 1975 to 1985, more pivotal changes took place in Singapore than in the whole thousand-year history of the island. There was a building boom, the economy grew phenomenally, the rivers and shores were cleaned up, and sufficient capacity was added to the sewage system to collect and treat all wastewaters from homes and industry. People developed physically, socially, and culturally.

In 1975, pig rearing was a backyard activity carried out the traditional way by the Chinese, who constituted over 80% of the population of Singapore. As is humorously depicted in a cartoon in Chapter 1 (Fig. 1.1), pigs were considered part of the Chinese household. As a matter of fact, the character for "home" in the Chinese alphabet is a pig sheltered by a roof.

Within a few years, pig rearing was transformed into a substantial commercial enterprise with some of the largest farms in the world. In 1983, a world record was established for distance traveled when a Boeing 747 loaded in Chicago with sows and boars landed in Singapore. The pigs were the nucleus of the breeding stock of a projected 120 000-pig farm, the largest of its kind, to be located within a fenced area of 600 000 m^2 (60 ha). The first and longest barns ever built on a 1% slope and equipped with an automatic flushing system became operational in 1982. The concept was copied in several other countries in the region. A unique total recycling system was conceived, built, and tested for a decade.

The Book

I have taken a novel approach in writing this book because I wanted to accomplish two objectives: to chronicle the consequential events of that decade of change and to pass on the experience to students and consultants who will be involved in similar undertakings in the future. Thus, I wrote the book as a textbook-cum-research report.

The only sources of material for the book are the 167 reports and memos generated by project staff. It was not practical to relate in this book all the topics that were studied or to report the subject matter in the depth of coverage given in the original papers.

When editing the voluminous reports of the projects, I tried to select data and papers that would present a complete picture of what happened, and at the same time, include work of universal application. There were time and space constraints in this effort. There was a 60% reduction in the size of the manuscript from the first to the last draft. Therefore, I might have omitted inadvertently or failed to even mention some crucial work in the final version of the book. If I had to do it over again, I would have started writing this book when the first project commenced and have made this book the final report. But, I did not have such foresight 15 years ago.

Although the book draws its material from work on pig excreta and pig wastewaters, the approaches and conclusions are applicable through appropriate professional judgement to all organic solid wastes and wastewaters.

This book was designed for use as a text in waste management courses for professional and graduate students, and in conjunction with other textbooks that cover the basics of animal waste management and treatment processes. If the book is used as the only reference in a university course, then the students should already have a basic course in environmental sciences and engineering and, therefore, be familiar with the basic concepts of waste treatment and with relevant terminology. The students should be upperclassmen in a professional degree program or graduate students.

The question and answer sections at the end of the first seven chapters are included to express expert opinions on some of the key issues, to serve as examples for reflection and reinforcement, and to aid in the development of professional judgement on the subject matter. There are no question and answer sections in the last two chapters because the subject matter of these chapters is highly technical and, as such, answers to all questions should be precise. It is intended that for these chapters, exercises be carried out to test the application of the formulas for sizing unit operations to the local conditions and to update the economic costs. Also, at the end of most of the chapters there is a list of forum ideas to be discussed in class or to be given as small assignments to relate the chapter contents to local situations.

The costs presented in the book must be updated and adapted to local conditions based on current unit prices and appropriate inflation factors.

Archives

For those who want to search and review the original sources, the papers are maintained in the library of the Pig and Poultry Research and Training Institute, Primary Production Department, Sembawang Road, Republic of Singapore. Copies of progress reports and of some of the technical reports can be located through the agencies that sponsored the work. To expedite the location of such reports it would be best to mention the specific projects: International Development Research Centre, Regional Office for Southeast and East Asia, Tanglin PO Box 101, Singapore 9124, Republic of Singapore (projects 3-P-85-0048, 3-A-89-4423, and others); Food and Agriculture Organization of the United Nations, Via Terme di Caracalla, Rome 00100, Italy (projects AG:DP/SIN 74/006 and AG:GCP/SIN/001/AUL); United Nations Development Programme, United Nations Plaza, New York, USA (UNDP/FAO Project SIN/74/006 and UNDP/FAO Project MAL/84/001).

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The generous support of the Government of Singapore, the United Nations Development Programme (UNDP), the International Development Research Centre (IDRC), the Food and Agriculture Organization of the United Nations (FAO), the Australian Development Assistance Bureau (ADAB), the German Agency for Technical Cooperation (GTZ), and the Association of South East Asian Nations (ASEAN) is gratefully acknowledged.

The contributions of the over 100 persons who were involved in the projects highlighted in this book are thankfully recognized. The most rewarding part of the whole experience was the team spirit and magnanimous cooperation of the individuals from the various agencies, including those who administered aspects of the project without coming into contact with the actual work in Singapore.

This book is a product of the inspired leadership of Dr Ngiam Tong Tau. Dr Ngiam became Director of the Primary Production Department of Singapore in 1984. He had served previously as comanager of the internationally funded projects. Dr Ngiam was instrumental in obtaining the support of IDRC in 1985 to use the waste biotechnology facilities developed in Singapore to train some 45 environmental engineers and scientists from ASEAN and other regions on the art and science of waste management. The visionary leadership and outstanding contributions of Dr Ngiam are gratefully acknowledged.

I would also like to acknowledge the contributions of Mr Lee Kam Wing of IDRC and Mr Yap Boon Chark of PPD whose collaboration and encouragement during preparation of the several drafts of this book went beyond the call of duty.

Chapter 1

A Summary of the Singapore Experience

This chapter presents an overview of the concepts and approaches considered in planning and integrating livestock production with environmental goals. General technical results of biotechnologies that were researched and tested in full-scale applications are illustrated with photographs, figures, and tables. The chapter highlights the period from 1975 to 1987 during which intensive pig feedlot farming areas were developed in two districts of the Republic of Singapore. Limited available land (5 m^2 per standing pig) and environmental pollution control constraints created unique situations and opportunities for research and development of pig housing facilities integrated with waste treatment, resource recovery, and recycle systems. The projects were funded by international agencies and the Government of Singapore. The chapter also delineates the major considerations both in the formulation of government policies on livestock production and in the reversal of these policies.

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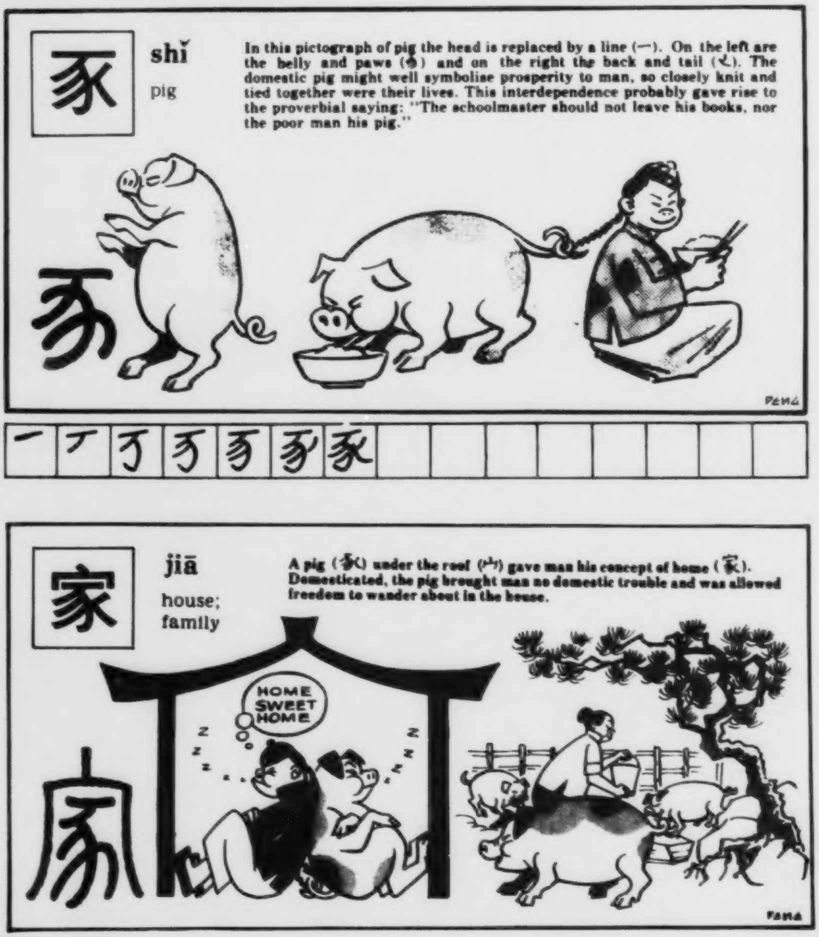
Historical Perspectives

Pigs were among the first animals to be domesticated. They are intelligent, clean, friendly, and relatively easy to train, and they make good pets.

Because they are monogastric (like humans), pigs are capable of using almost all the food materials discarded by man. As scavengers, pigs have lived almost symbiotically around human settlements and have provided humans with greasing lard, meat, fertilizer, and even pigskin for shoes and clothes. In return, human settlements provided pigs with food and protection from their many predators.

In Asia, pigs were associated with rituals and ceremonies and constituted the main source of meat. In China, the cultural importance of the pig has been especially evident, as is aptly demonstrated in Fig. 1.1.

Today, in many parts of the world, and particularly in China, many households keep pigs within their housing compound and feed them kitchen and grain leftovers. For large farms, restaurant leftovers and



In this pictograph of pig the head is replaced by a line (一). On the left are the belly and paws ([illegible]) and on the right the back and tail (乚). The domestic pig might well symbolise prosperity to man, so closely knit and tied together were their lives. This interdependence probably gave rise to the proverbial saying: "The schoolmaster should not leave his books, nor the poor man his pig."

A pig (豕) under the roof (宀) gave man his concept of home (家). Domesticated, the pig brought man no domestic trouble and was allowed freedom to wander about in the house.

Fig. 1.1. Traditional standing of the pig in Chinese lore (reproduced from *Fun With Chinese Characters, Volume 1* with permission of Federal Publications (S) Pte Ltd, *Cartoonist:* Mr Tan Huay Peng).

by-products of milk-processing plants are collected, cooked, and fed to pigs. However, this ancient recycling process creates a serious side effect.

The scavenging of pigs around human settlements must have created one of the first public health issues, trichinosis. Trichinosis is a muscle debilitating zoonotic disease caused by a parasite, *Trichinella spiralis*, which infects humans when they consume infected pork that has not been well cooked. Infected humans contaminate the food leftovers and, when these are eaten by the pigs, the parasitic organism deposits itself in the muscles of the pig. Thus, the disease could be retransmitted by the consumption of infested pork flesh that had not been cooked long enough to kill the pathogen.

This vicious cycle of cross-contamination was broken in some communities that insisted that only well-cooked pork be eaten; in others, religious edicts were used. The Jewish and Islamic faiths, both of which originated in the warm climates of the Middle East where trichinosis was rampant, prohibited the rearing of pigs and the consumption of pork.

Pig Production Trends

Scientific discoveries in breeding, surplus grain production, and many other factors stimulated the commercial production of pigs. Commercial pig farming areas began to expand in the 1960s and spread before any zoning or environmental controls could be applied. As demand for pork began to grow with the economic boom of the 1970s, pig farms expanded into large commercial units. Table 1.1 shows that the standing pig population (SPP) of the world increased from less than 500 million in 1965 to almost 800 million in 1985. At the same time, the number of pig farms decreased significantly.

Based on statistics maintained by the Food and Agriculture Organization of the United Nations (FAO), China had the world's largest population of pigs in 1985 with over 300 million SPP, which represented 38.6% of the world's 800 million SPP. Although only 6 countries (Brazil, China, Poland, the Soviet Union, the United States, and West Germany) had more than 10 million pigs in 1965, this number increased to 13 in 1985 with the addition of East Germany, France, Japan, Mexico, the Netherlands, Romania, and Spain. (West and East Germany both had over 10 million pigs in 1985; united, Germany now has the fourth largest pig population in the world.)

In 1985, Asia had 48% of the world's SPP and was the region with the largest annual growth rate in pig population (4.7% vs 3% for the rest of the world). The countries with the highest annual growth rates were Netherlands (9.9%), Spain (9.2%), Japan (7.6%), Romania (7.3%), East Germany (7.3%), Mexico (5.4%), and China (5.1%). The only country with a negative growth rate was the United States.

About 48% of the SPP is located in countries with warm climates

Table 1.1. World standing pig population (SPP) in 1965 and 1985.

	1965		1985		Growth, 1965–1985	
Region	SPP ('000)	% of total	SPP ('000)	% of total	Total (%)	Annual (%/year)
Continents						
Asia and the Pacific	195350	39	379870	48	94	4.7
Europe (including USSR)	170980	35	257770	32	51	2.5
North America (including Mexico)	72120	15	83750	11	16	0.8
South America	48740	10	59500	7	22	1.1
Africa	5980	1	10780	1	80	4.4
Oceania	2400	<1	3030	<1	26	1.3
World total	495570		794700		60	3.0
Warm/tropical regions						
Asia and the Pacific (excludes 30% of SPP of China and 100% of Japan)	149570	30	284620	36	90	4.5
Europe	—	—	—	—	—	—
North America (30% of USA and Mexico)	27700	6	35180	4	27	1.4
South America (excludes Argentina, Chile, and Peru)	42020	8	52450	7	25	1.2
Africa (excludes South Africa)	4580	1	9350	1	104	5.2
Oceania (50% of Australia and New Zealand)	1200	<1	510	<1	26	1.3
Subtotal	225070	45	383110	48	70	3.5

(Table 1.1). Of the 172 countries and territories that raise pigs, the 13 countries that had an SPP of more than 10 million accounted for 75% of the world's pig population.

Environmental Constraints

Based on a pollution population equivalent of 2.5 humans per pig, the water pollution potential in 1985 of the world's 800 million pigs was equal to that of more than 2 billion humans or 40% of the human population of the world.

From 1965 to 1985, public awareness of the effects of pollution and universal demands for preservation of the quality of the environment increased significantly. This placed urgent demands on the pig farming industry to control pig waste discharges. The traditional methods of disposing of manures in cropland were no longer adequate or suitable for the new, large, intensive pig farming enterprises. There was a dearth of scientific and engineering experience derived from full-scale, long-term experiments in animal production and pollution control.

Aside from economic considerations, what constrains the development of the pig industry in both temperate and tropical zones is its environmental impact. There are three features of pig farming that have negative impact:

- water pollution from pig wastes,
- malodours emanating from pig farms, and
- religious sensitivities to pigs.

Environmental concerns restrict many countries that want to expand their pig production. However, the limitations differ from country to country. For example, in the Netherlands, concern over a build-up of nitrates in soils because of high rates of manure application resulted in severe restrictions being imposed on livestock production. Pig farming was allowed only on existing farms that had access to a specified amount of land (25 pigs/ha of cropland or 400 m^2/SPP). The development of new pig farms was halted in 1985.

In highly urbanized countries like Singapore, with severe land constraints, stocking density was as high as 2 000 pigs/ha (i.e., only 5 m^2/SPP). Moreover, farms could not be less than 1 000 m from the nearest residential area, which, by 1983, was impossible in the remaining non-water-catchment areas of the city-state. In Hong Kong, even small farms are required to install treatment plants to meet 50/50 mg/L BOD/TSS effluent quality standards. In Malaysia, where the state religion is Islam and the pork-consuming population is less than 50%, pig farming is restricted to sites zoned for pig production and standards of zero waste discharge are imposed because of religious objections to pigs.

Although these examples may appear unique, they represent what will be the case in many parts of the world in the near future. That is why it is important to document the history of the Singapore experience.

The Singapore Experience

This book is based on engineering research and development carried out in Singapore. During the 13 years from 1974 to 1987, pig farming in Singapore was completely restructured and a wide spectrum of ideas and technologies was researched at laboratory, pilot, and field-scale plants.

The city-state of Singapore has a total land area of 620 km^2 and is located near the equator in Southeast Asia (Fig. 1.2). The climate is tropical, with daily temperatures of 21 to 31°C and relative humidities of 70 to 100%. Although rain may fall more frequently during November and December, the possibility of showers is 50% on any given day. The annual rainfall is 2 000 mm.

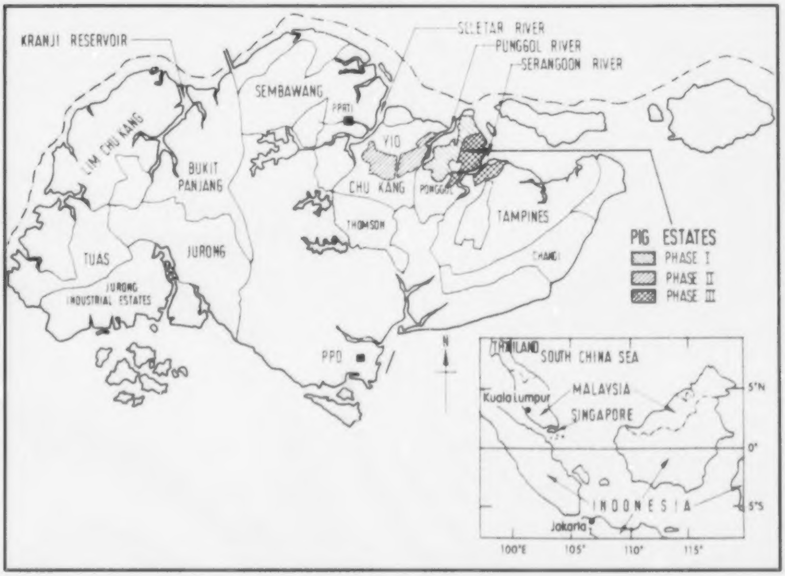

KRANJI RESERVOIR
SELETAR RIVER
PUNGGOL RIVER
SERANGOON RIVER
SEMBAWANG
PPRTI
LIM CHU KANG
BUKIT PANJANG
YIO
CHU KANG
PONGGOL
TAMPINES
THOMSON
TUAS
JURONG
JURONG INDUSTRIAL ESTATES
CHANGI
PPD
PIG ESTATES
PHASE I
PHASE II
PHASE III
N
THAILAND
SOUTH CHINA SEA
MALAYSIA
Kuala Lumpur
SINGAPORE
INDONESIA
Jakarta
5°N
0°
5°S
100°E
105°
110°
115°

Fig. 1.2. The Republic of Singapore, showing the location of the pig estates, the Pig and Poultry Research and Training Institute (PPRTI), and the Primary Production Department (PPD) of the Ministry of National Development.

Singapore's 2.5-million population is multiracial (78% Chinese, 15% Malay, 5% Indian, and 2% others). All the Malays and 3% of the rest of the population profess the Muslim religion, which forbids the consumption of pork and of any substance that contains any derivative of pigs. Muslims must not come into contact with pigs or handle water that has received pig waste. For the Chinese, on the other hand, pork is an indispensable part of their daily diet; they consume over 35 kg/person annually.

Most of the agricultural districts in Singapore were converted into new towns of multistory residential housing estates that encroached on the pig feedlot farming areas (PFAs). The studies on layout of PFAs and waste resource recovery were carried out at two stations of the Primary Production Department (PPD): the Pig and Poultry Research and Training Institute (PPRTI), located in Sembawang, and the Ponggol Pig Centre (PPC) (Fig. 1.2).

Transformation of Pig Farming

Pig farming in Singapore was transformed from a backyard activity of part-time subsistence farmers averaging less than 100 pigs per farm to a modern industry of full-time farmers operating commercial units of 45 000 SPP (see Fig. 1.3). This transformation was a result of government policies

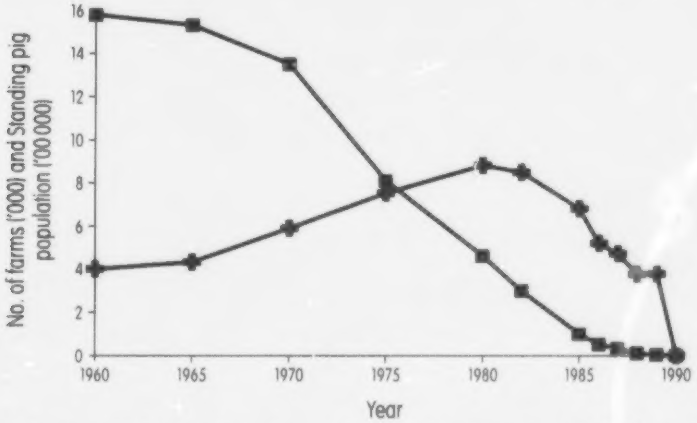


Fig. 1.3. Changes in standing pig population (✚) and number of pig farms (■) in Singapore from 1960 to 1990.

implemented with the technical and financial assistance of international agencies.

In 1974, the SPP of Singapore was about 750 000, scattered throughout the island republic in over 9 000 farms. Over 70% of the pigs and 6 000 farms were located within water-catchment areas. Less than 50 farms had more than 1 000 pigs. A decade later, 10 commercial farms, established under engineering and architectural standards, averaged over 15 000 SPP/farm and covered an area of 80 ha with a stocking density of 2 000 SPP/ha. By 1990, in a reversal of government policy, all pig farming was phased out.

In the 1970s, as was the case everywhere in Asia, pig farms in Singapore were scattered throughout the rural countryside. However, some of the livestock farms were located within urban areas and, as noted earlier, most of them were within watersheds that were used as catchment areas for public water supply. Ozone disinfection had to be introduced in the water-treatment plants to ensure bacterial and viral safety of public water supplies. For this and many other reasons, Singapore experimented with policies and actions to help guide future commercial pig farming projects both in Singapore and in other countries that were considering intensive livestock production.

Intensive Pig Farming

Beginning in 1967, the Government of Singapore sought and received the cooperation and technical assistance of the United Nations Development Programme (UNDP) and other international agencies to initiate a series of projects to intensify pig and poultry production. By introducing scientific least-cost feed formulations, upgrading animal husbandry and veterinary health practices, and improving the layout of farms and the design of production facilities, the foundations for the commercial expansion and intensification of pig and poultry production were set in the 1970s. Singapore achieved self-sufficiency in eggs, poultry meat, and pork. But, the single largest and most vexing problem with pig farming was the disposal of solid wastes and the pollution caused by pig wastewaters and pig farm malodours.

With the establishment of the Ministry of the Environment in 1969 and the promulgation of effluent water quality standards in 1976, the Government of Singapore embarked on a comprehensive program to abate pollution from all industrial sources. By 1980, industrial plants had to install on-site pretreatment facilities before discharging wastes into regional sewage-treatment plants built by the government. Moreover, rivers and estuaries were being cleaned by building interceptor sewer lines and by dredging bottom sludge. Pig farming was not exempt from this mandate to control pollution.

The first steps taken to alleviate the problem of water pollution from pig farms were temporary. One measure was to cease the rearing of pigs in all farms within water catchment areas. This was successfully completed by 1981. Another measure was to identify less-sensitive areas where pig farming could be carried out over a period of years until a permanent solution could be formulated. Farmers were resettled to noncatchment sites that were designated as intensive pig farming areas for a 30-year period.

At the same time, the government sought and received financial and technical assistance from UNDP, FAO, Canada's International Development Research Centre (IDRC), the German Agency for Technical Cooperation (GTZ), the Australian Development Assistance Bureau (ADAB), regional projects of the Association of South East Asian Nations (ASEAN), and others to carry out research and development programs in animal production combined with waste management and utilization.

Farm Resettlement

Starting in 1975, pig farmers were resettled from the water catchment and urban areas to Ponggol district in the central north tip of Singapore (see Fig. 1.2). About 650 ha of land was developed into intensive pig farming lots. Ponggol Phase I pig farming estate (208 ha) was established in 1974–75. This was followed by the development in 1975–76 of Jalan Kayu Phase II pig farming estate (253 ha). At both of these sites, minimal earthworks were carried out. Roads were not paved until a few years later, but concrete drains were installed to carry both rain runoff and farm effluent. The incoming farmers carried out their own earthworks at the farm lots before erecting their pig barns and family dwellings.

The PFA layout of Phase I and Phase II was planned for small lots specifically to encourage family farms. However, some sites at Ponggol

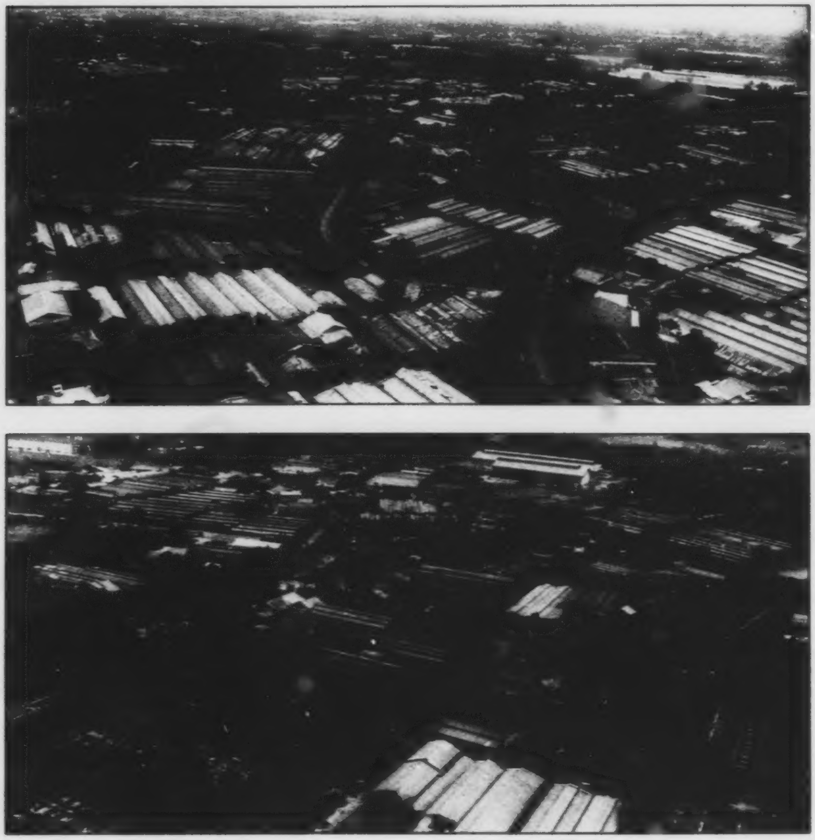
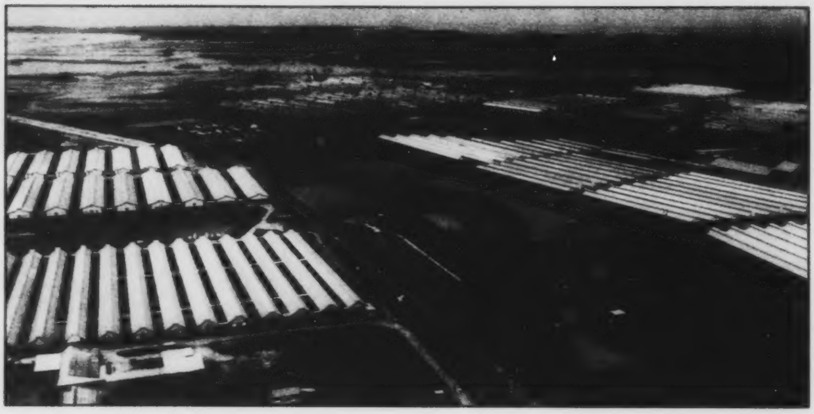


Fig. 1.4. Ponggol PFA Phase I as it appeared in 1985. The upper photo shows the northern section of the PFA looking east toward Phase III; the lower photo is looking south. Note the congested layout and divergent orientation of the barns in Phase I and compare with the east–west orientation and narrow barns of Phase III in Fig. 1.5.

Phase I were made available for commercial pig farming. Commercial farmers were given long-term leases (30 years) and were charged commercial rates for land rental. Small farms were given temporary occupation licences with nominal rental charges but were obligated to renew their licences periodically. Farmers made intensive use of the land to build pigsties with little regard for proper farm layout, sanitation, or esthetics.

Allocation of land at Jalan Kayu PFA was stopped in 1978 because of complaints that malodours from the pig farms affected the nearby residential estate. Figure 1.4 is an aerial view of the farms of Phase I as they looked in 1985, 10 years after the resettlement exercise.



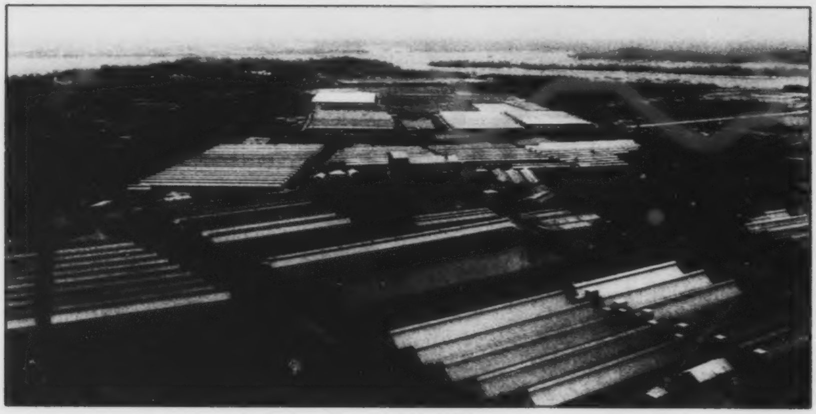


Fig. 1.5. Ponggol PFA Phase III. The new long and narrow barns are built on a 1% slope for waste removal by flushing. Water ponds used to harvest and store rainwater for hosing the pens are shown along with an oxidation ditch that was under construction in 1985. In the lower photo, Phase I buildings are in the bottom right foreground. Note not only the change in width and uniformity of length of the buildings, but also the high density in both cases (compare with Fig. 1.4).

There were inherent shortcomings in encouraging the development of small farms. Most of the farmers installed cheap feed-milling machinery on their farms and experienced difficulty in producing quality pig feeds. There was lack of economy of scale. The farmers brought with them traditional practices that included old building materials and wide barns, and they did not improve their housekeeping and husbandry practices.

It was this early experience in the first two phases of the Ponggol intensive pig feedlot farming areas that led to engineering research to develop a comprehensive plan for the full development of Ponggol Phase III PFA (Fig. 1.5).

The overall concept of Phase III PFA was to create an industrial parkland for pig farming that was surrounded by thick belts of trees to buffer the area from the surrounding residential areas. Trees were planted on both sides of farmways and along the public highway. Landscaping reduced the severity and impact of the farm structures.

To control movement into and out of the Phase III PFA, only two entry points to the estate were constructed. The layout of the lots provided for separate drainage of surface runoff in roadside drains and for farm waste drainage from the back of the farm lots to a canal. The farmways were designed with adequate width and loading capacity to facilitate feed delivery by heavy vehicles. The farmways had 7.4-m paved carriageways and 2.5-m service verges on both sides. Fast-growing trees were planted on the service verges.

Pig Farming Policies

By the end of the 1970s, waste-treatment technology and infrastructure developments in the pig industry warranted the establishment of a policy for commercial pig farming in Singapore. The pig farming policies and waste technologies of countries in North America, Europe, and Asia were studied. Large commercial farms equipped with pollution-control plants existed only in northern Italy, the socialist countries of Eastern Europe, and Japan. These countries were visited by several project study teams.

The total initial cost of all the treatment systems studied in Japan ranged from 54 to 150 USD/SPP (1980 dollars). The least-cost systems were the standard activated sludge plants when compared with the chemical or composting plants that were visited. Highly mechanized compost plants were found to be the most expensive. Annual operating costs varied from 5 to 19 USD per standing pig marketed (SPM). Total operating cost, which included a capital recovery component over a period of 15 years (average 7 years for equipment and 25 for facilities), ranged from 21 to 54 USD/SPM.

The incentives granted by the Japanese government to develop composting systems for solids encouraged Japanese farmers to team up with engineering firms and contractors to develop, build, and operate prototype waste-management systems. From 50 to 70% of the capital cost was provided by central and prefectural government grant schemes; the rest could be obtained by the farmers as low-interest loans. The study team concluded that the selection of waste-handling systems in Japan was not based on treatment needs and requirements but rather on government subsidies.

In developing the Singapore policy, the urgent issues to be considered were

- food supply security for the island's population,
- demands for fresh pork (annual consumption had risen to 35 kg/person),
- demands for the use of land for housing and industrial estates,
- limits on water supply (the majority of the water needs were being met by long-term contractual agreements with Malaysia),
- keeping the environment clean with no sector exempt no matter how vital to the nation,
- preference of Chinese consumers for lean meat and their distaste for frozen pork,
- public health,
- regional political considerations (all neighbouring countries had agriculture-based economies and were keen to develop an export market to Singapore for meat, vegetables, and poultry products,
- the religious sensitivities of the Muslim population to pigs and pig-waste pollution of estuary waters, particularly in the late 1970s when religious fundamentalism was becoming established in Malaysia and Indonesia, and
- social considerations and the public nuisance of animal malodours.

First, the policy adopted by the Government of Singapore stated that the total pig population was to be reduced to 60% of self-sufficiency in pork. This stimulated commercial pig production in neighbouring countries and ensured a competitive supply of live pigs for Singapore. A 40% reduction in SPP could be conveniently met by phasing out farms in Jalan Kayu PFA, which were too close to residential estates, and other farms that had no land for the installation of pollution-control facilities.

Second, pig farming on the island of Singapore was to be totally phased out by 1995. Farms choosing not to accept compensation but to continue rearing pigs until 1995 had to become incorporated. This provision, compounded by government policies to restrict employment of foreign workers, stimulated automation on the farms and the upgrading of husbandry practices and breeding stock.

Farmers had to upgrade their skills to remain competitive. Through the government-sponsored skills-improvement scheme and courtesy of equipment sales companies, farmers toured Asia, Australia, Europe, and the United States to get ideas for the design of their new barns and waste-treatment facilities. Short courses and seminars were arranged for professional engineers and architects to introduce the design of least-cost farm structures and farm layout. Farmers were required to employ professionally registered engineers and architects to produce farm layouts and structures.

Third, in the intervening 10 years, pig farms had to become incorporated, and the company had a legal responsibility for meeting effluent standards. Farmers were required to construct treatment plants for which they could get capital grants from the pig environmental pollution fund. This particular provision of the policy stimulated the development and testing of full-scale waste-treatment plants. The demonstration plants would not only help Singapore farmers, they would also be a source of information on fully tested treatment technologies for the neighbouring countries that were expected to increase their pig production to cater to the Singapore market.

Details of the pollution-control requirements are presented in Table 1.2. Note that the regulations are specific for both liquid and solid discharges. The latter presented the greatest challenge because of the severe constraints of land and religion.

Construction Grants

Envisioning that eventually there would have to be pollution control regulations, the Government of Singapore imposed an environmental levy on pigs to create a fund to entice farmers to construct high-quality waste-treatment facilities. The money for this environmental pig fund was derived from a levy of 5 USD per pig slaughtered at the two abattoirs. The levy was imposed on all of the more than 1 million pigs slaughtered every year, including those imported from Malaysia and Thailand. It was put into effect at the beginning of 1980 and accumulated at the rate of more than 5 million USD/year. The fund was projected to reach over 30 million USD by the end of 1985, when payments were to be made after the completion of approved on-farm treatment plants.

Qualifying farmers, 62 of them, were given capital grants of 50 USD/SPP for the design and construction of waste-treatment facilities. To be eligible for the Capital Grants Scheme (CGS), the treatment facilities would have to meet discharge standards.

Discharge Standards

Effluent standards, conditions, and requirements were released in May 1982 as *Guidelines for the Planning and Construction of Pig Farm Waste Treatment Systems*. The key parameters for liquid and solids treatment were

- a 5-day biochemical oxygen demand (BOD_5) of 250 mg/L, which represented a 95% reduction from the BOD_5 of the raw wastewaters,
- a sludge of at least 20% total solids content (TTS),

Table 1.2. Summary of pig waste control regulations for Singapore PFAs.[a]

Control parameter	Requirements, expectations, explanations
Wastes to be treated	All fecal excretions and wastewaters generated on pig farms must be treated (i.e., both solids and liquids) in a manner that will not create a nuisance or fly breeding conditions.
Liquid discharges	All liquid discharges must be free of settleable materials, floating debris, scum, oils, and other foreign materials that would be unsightly or create odour and other public nuisances or form putrescent or otherwise objectionable conditions.
Effluent BOD_5	From 1 January 1985 (3 years later), BOD_5 of the liquid effluent from all farms must not exceed 250 mg/L at any time. (After assessment of the success of the program, stricter standards of 50 mg/L BOD_5 would be enforced by the Ministry of the Environment at a time that was to be decided. Therefore, designers made provision for such eventuality in their proposals. The 250 mg/L standard was based on 95% pollutant reduction, assuming the wastewater generated averaged 5 000 mg/L BOD_5; in terms of daily mass rate of 20 L/SPP, daily BOD discharge per pig is 5 g/SPP, which would be equivalent to 25 mg/L BOD_5 standard per person in terms of human sewage. In Singapore, each person produced more than 200 L of sewage per day.)
Discharge point	All liquid effluents must be discharged from a single point into an approved watercourse, public drain, sewer, or natural waterway.
Solids treatment	Solid wastes shall be stabilized so as to reduce the total volatile solids (TVS) concentration to not more than 70% of total solids (TTS) on a dry weight basis. (This requirement could best be met through anaerobic digestion in a deep lagoon or a biogas digester, processes that preserve the nutrient value of the waste and facilitate energy recovery.)
Solids storage	Stabilized solids and sludges must be stored properly on the farm without creating public nuisances or fly breeding conditions. (The best and simplest way to achieve this would be windrow composting.)
Solids transport	All waste solids and sludges removed from the farm for disposal at approved landfill sites must have a moisture content of less than 80% (i.e., TTS must be more than 20% on a wet weight basis). (This could be achieved with sand filter beds or with decanters only if the sludge was stabilized and decomposed as suggested above.)

(continued)

Table 1.2 continued.

Control parameter	Requirements, expectations, explanations
Solids disposal	Government-operated landfill sites approved for disposal of stabilized solids and sludge will be provided. (This was necessary in Ponggol where the farm lots provided only 5 m^2/SPP with no other land available except government land being reclaimed from the neighbouring swamps.)
Effluent monitoring	All farms with more than 5 000 SPP will be required to install a flow-measuring device before their discharge outfall, which would facilitate daily sampling of their effluent. All other farms with less than 5 000 SPP will be sampled with random, spot, grab samples as deemed necessary.
Monitoring frequency	When a farm is found in noncompliance with the 250 mg/L BOD_5 standard, the farm effluent will be monitored daily and the farmer may be requested to install at his expense a 24-h continuous monitoring device.
Treatment technologies	Farmers are free to select any of the wastewater-treatment facilities being marketed or recommended by a consulting engineer or qualified company.
Engineering plans	Engineering plans for the construction of treatment facilities and waste-delivery systems should be prepared by qualified people or companies considering the unique features of pig wastewaters and the pig-management practices in Singapore. (This was to prevent companies from making the mistake of using without adequate adjustments manure- or sewage-treatment technologies used in other countries and climates.)
Designer qualifications	Plans and drawings should be prepared under the supervision of professional engineers registered for practice in Singapore. (This was another way to protect the farmers' interests from unscrupulous sales people.)
Qualified companies	Companies that have qualified staff and documented relevant experience or are associated with a well-qualified foreign company may undertake the design and construction of the plant. Such companies shall be required to post a performance bond for any turnkey plants. (These precautions were stipulated to protect the farmer and the grant money given to farmers to pay such companies under CGS.)
Flow chart	Drawings showing the flow of materials plus a layout of the major components of the treatment plant showing waste stream quantities in and out of each major operation.

(continued)

Table 1.2 concluded.

Control parameter	Requirements, expectations, explanations
Construction drawings	Construction drawings and written specifications for the entire treatment plant showing all dimensions, and specifying materials and equipment for the treatment of wastewater, the separation and stabilization of the solids, and the handling and disposal of the sludge.
Relevant calculations	Engineering calculations used in the design of the various processes with expected results and brief delineation of the reason for choosing the system over other options considered should be submitted.
Minimum facilities	On the new farms, where flushing is to be used for wastewater delivery and where no provisions are made for wastewater storage under the floor or outside the barn, a lagoon with capacity of no less than 1.25 m^3/SPP must be provided irrespective of the treatment technology used. (This provision was included to ensure that during equipment repairs, flood rains, etc., the wastes were not discharged untreated.)
Amount of grant	Capital construction grants will be allocated at the flat rate of 50 USD per standing pig population per farm or group of farms organized into a single wastewatershed unit for the purpose of building and operating a common treatment plant.
SPP determination	The procedures for determining the SPP are based on a stocking density of 2 000 SPP/ha and calculated by multiplying the number of pen spaces assigned to sows by a specified factor. (In the case of Singapore, the multiplying factor was 10.5 and 12 times the spaces for dry sows and gilts for the minimum and maximum SPP, respectively. Provision was made for individual farm calculations. Treatment plants had to provide for the maximum SPP, but could be designed for the mean SPP; the lagoon requirements above could be used to stabilize the flow rate into the treatment plant and thus cater to the invariable variations in the quantity of waste generation.)
Grant approval	Application for a capital construction grant shall be submitted by each farmer or group of farmers for technical and administrative review by the technical subcommittee. Eligibility for a construction grant of 50 USD/SPP shall be determined by the disbursements committee, consisting of officers from Primary Production Department and Public Works Department of the Ministry of National Development, the Ministry of the Environment, and the Ministry of Finance.

[a] This table presents the waste control requirements and a summary of other features from the planning and construction of pig farm waste treatment systems as promulgated in 1982. The guidelines included a timetable, design information on the farms, procedures for calculating SPP, waste data, etc. Based on the Singapore experience, typical regulations that may be adapted elsewhere have been developed.

- sufficient reduction in the organic content of the solids to produce a total volatile solids (TVS) to TTS ratio (TVS/TTS) of less than 70%, and
- design flexibility for future additions that would facilitate higher quality liquid effluent.

Although the guidelines suggested an acceptable modular waste treatment (MWT) system based on a deep anaerobic lagoon, farmers were free to choose whatever system they wished from any qualified firm anywhere in the world.

Treatment Technologies

After the announcement of the scheme of grants, about 100 companies from around the world converged on Singapore to extol their hardware and services. Of the 100 companies that indicated interest, 40 participated in a seminar/exhibition in 1982, 22 submitted detailed proposals for specific farms, and 13 won contracts from farmers. It is not assumed that the companies that came to Singapore or participated in CGS through local intermediateries represented the full spectrum of technologies or necessarily the best in the market. However, their processes represented the full spectrum of technology available at the time.

To be considered under CGS, proposals had to be for a specific farm and had to detail how the system would meet the effluent standards of 250 ppm BOD_5 at first (50 ppm eventually) and stabilize the solids. The proposals were prepared by commercial firms, not by independent consulting environmental engineers, except for a few cases.

Within 4 months (by December 1982) some 278 proposals from 22 firms for 62 individual farms were reviewed and classified by a technical committee consisting of government and United Nations experts. The annual cost of meeting the 50 ppm BOD_5 standard by the proposed time was calculated as 10.96–18.13 USD/SPP. The most probable mean was estimated to be 14.80 USD/SPP or 9.25 USD per porker marketed per year (PMY). The initial cost of construction was assumed to be 50 USD/SPP in all cases, and this was to be paid by a grant under CGS. Policy strategies were based on less than 10 USD/SPM for pollution control, which PPD projected would still keep pig production in Singapore competitive compared with live pig importation.

Classification of Proposed Designs

An examination and, in many cases, site inspection of the technologies offered by the majority of the companies showed that their systems were not designed for tropical climates and would not be suitable for the scale and conditions of the Singapore farms. It was necessary, therefore, to classify the proposals into three major categories to allow farmers to assess the technical merits of the processes. It should also be noted that the claims of some companies could not be substantiated with objective data. The proposals were classified as A, A–, B, or C.

Class A

Process design was fairly complete in terms of flow chart details, sufficient calculations to indicate adequate understanding of the system, and sufficient evidence that the process could achieve the projected effluent standards. If it was nonconventional or proprietary, the process had been tested and had met specific effluent standards in the treatment of pig waste elsewhere.

Class A–

Design could meet effluent standards but needed to be reviewed once more after submission of additional data and consultations with the designers. In some cases, the cost of the process, judging from what had been submitted, appeared excessive in terms of initial costs, operating costs, or both. In some cases, the proposed process was not appropriate to the specific farm. The system also might have been excessive for the level of treatment required.

Class B

Although process design was sufficiently detailed as far as the flow charts were concerned, the calculations of the process design were either insufficient or contained questionable figures or unit operations. These systems were not recommended unless the designers provided evidence of experience or relevant technical capability to modify the design to meet treatment requirements.

Class C

Process design was based on proprietary technology that had not been tested or shown to meet specific effluent standards in pig waste treatment. Or, the design might be based on conventional technologies that were adopted by companies that could not present evidence that they had both the technical expertise and relevant experience to assure satisfactory commissioning of the plant.

Demonstration Plants

Class C companies that believed that their process would work were permitted to install, at their own cost, a plant for a consenting farm in Phase I PFA (see Fig. 1.2). Here, the farms were small and the plant had to be run at full capacity for a minimum of 3 months before the suitability of the system was assessed. If the plant met all the treatment requirements and was acceptable to the farmer, the farmer was eligible to apply for a construction grant for the plant under CGS. Otherwise, the company had to remove all equipment and facilities from the farm at no cost to the farmer.

Four private companies built full-scale plants at their own expense to demonstrate the suitability of their processes. Two others built pilot plants.

Compliance Certification

The procedures for the certification of a plant's compliance with the effluent standards were as follows:

- The company that proposed the plant carried out its own sampling over a period of 3 months and submitted an engineering report.
- The Government Technical Committee conducted its own sampling twice per week (8-h composite samples for a period of no less than 6 weeks; the program also included a 24-h composite sample).
- The plant met the standards when the test results fell within the limits either 100% of the time in the composite samples, or at least 85% of all the sampling times including grab samples. The maximum BOD_5 of any composite sample could not exceed 400 mg/L and any grab sample could not be more than 600 mg/L. At least 85% of all the samples had to exceed a TTS content of 20% and have a TVS/TTS ratio of less than 70%.

Public Plants

To ensure that the full spectrum of technologies and potential ideas of resource recovery and waste reuse and recycle were studied objectively, full-scale plants were constructed with partial funding from international agencies. This allowed for the development of pragmatic standards of performance for achieving practical effluent and water quality standards and for the training of future operators of such systems.

The operations of these demonstration plants for many years have produced data and experience that, along with the reports generated by numerous experts, are the subject of this book.

Research and Development Projects

Research and development (R&D) projects were designed to meet the specific needs of Singapore, i.e., pollution abatement, malodour management, resource recovery, and new housing designs to accommodate waste-management schemes. Surveys to define the nature of these problems were conducted before a decision was made on the specific projects to be undertaken. The first experimental facilities were located at the Pig and Poultry Research and Training Institute (PPRTI) (Fig. 1.6).

Criteria for the selection and evaluation of the R&D projects were technical, environmental, and economic feasibility, considered in that order of priority. The entire R&D program was guided by the principle that the technical soundness of the process would be ascertained first with full-scale field tests. Once shown technically possible, the process would be assessed for environmental impact, i.e., level of pollution reduction and

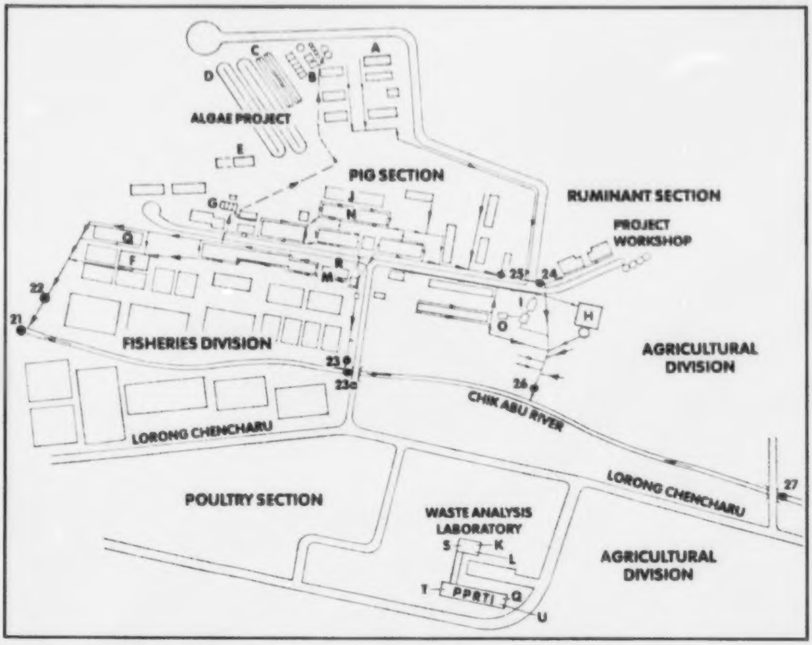

A
B
C
D
ALGAE PROJECT
E
PIG SECTION
G
J
N
RUMINANT SECTION
PROJECT WORKSHOP
Q
F
R
M
25
24
22
21
I
O
H
FISHERIES DIVISION
AGRICULTURAL DIVISION
23
23a
26
CHIK ABU RIVER
LORONG CHENCHARU
LORONG CHENCHARU
27
POULTRY SECTION
WASTE ANALYSIS LABORATORY
S
K
L
T
PPRTI
Q
U
AGRICULTURAL DIVISION

Fig. 1.6. Experimental facilities and pilot plants at PPRTI: A, pit aeration/bacterial protein; B, primary treatment plant/digesters; C, pilot high-rate algae ponds; D, demonstration ponds/algae; E, harvesting and office building/algae; F, diffused aeration/pisciculture; G, mini-ponds/bag digester; H, surface aeration treatment; I, cesspit digester/solids filter; J, solid fermentation; M, digestibility trials; N, cellular protein/feeding trials; O, waste composting; P, waste ensiling; Q, odour control; R, electricity network; S, waste analysis; T, staff offices; U, waste feed value profile; •, sampling points; arrows show direction of waste flow; dashed line shows underground pipeline.

quality of the liquid and solid discharges. Economic feasibility was determined in terms of capital and operating costs and economic impact on pig farming.

Because pollution controls add to the cost of production, it was necessary to develop ways to improve productivity and develop resource-recovery technologies to compensate for these higher costs. Surveys and projects were carried out on husbandry practices and on the design of housing facilities and farm layouts. The pathways of waste recovery that were studied are shown in Fig. 1.7.

Pig wastes and organic wastewaters in general contain three resources (water, nutrients, and energy) that can be recovered and recycled (Fig. 1.7). Singapore, a net importer of these three resources, was an ideal place for research. Animal waste utilization and recycling has always been a highly developed art in Asia. In small, mixed farming units, pig wastes flow into

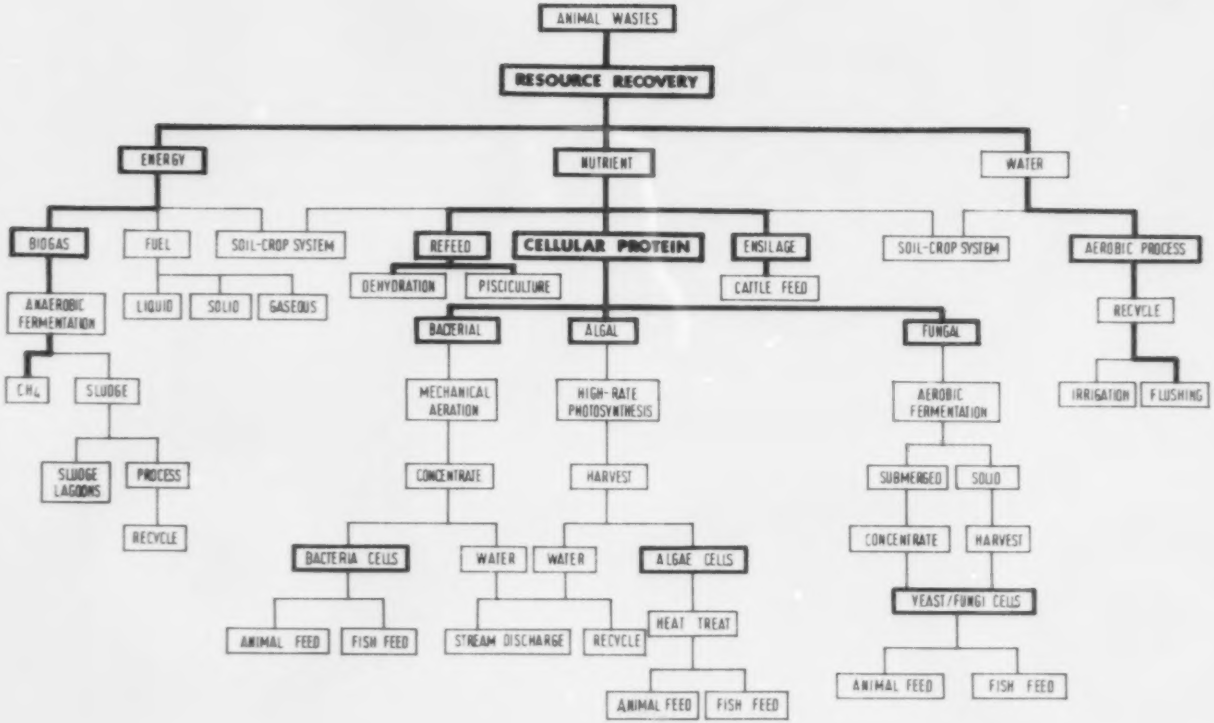

ANIMAL WASTES
RESOURCE RECOVERY
ENERGY
NUTRIENT
WATER
BIOGAS
FUEL
SOIL-CROP SYSTEM
REFEED
CELLULAR PROTEIN
ENSILAGE
SOIL-CROP SYSTEM
AEROBIC PROCESS
ANAEROBIC FERMENTATION
LIQUID
SOLID
GASEOUS
DEHYDRATION
PISCICULTURE
CATTLE FEED
RECYCLE
CH4
SLUDGE
BACTERIAL
ALGAL
FUNGAL
IRRIGATION
FLUSHING
MECHANICAL AERATION
HIGH-RATE PHOTOSYNTHESIS
AEROBIC FERMENTATION
SLUDGE LAGOONS
PROCESS
CONCENTRATE
HARVEST
SUBMERGED
SOLID
RECYCLE
CONCENTRATE
HARVEST
BACTERIA CELLS
WATER
WATER
ALGAE CELLS
YEAST/FUNGI CELLS
HEAT TREAT
ANIMAL FEED
FISH FEED
STREAM DISCHARGE
RECYCLE
ANIMAL FEED
FISH FEED
ANIMAL FEED
FISH FEED

Fig. 1.7. Waste resource recovery pathways. The heavy lines indicate the main pathway studied in Singapore through pilot and full-scale plants on both government and private farms.

ponds where fish, ducks, and vegetables are cultivated. The traditional, and arguably the best, method of abstracting resources from animal manure has been the utilization of organic wastes on cropland. In land-limited Singapore, where only wire fences separated pig houses, the ancient art of recycling had to be upgraded to suit the land constraints of modern livestock farming.

Pollution Control

Pollution control was a new requirement and added to the cost of production. The recovery of water, energy, and nutrients could not be justified solely on economic returns, despite many claims to the contrary. It made sense, therefore, to select pollution-control processes that facilitated the recovery of resources.

Nutrient Recovery

The most important element to be recovered in the biomass produced from the wastes was nitrogen. It was necessary, therefore, that animal-production pens be engineered to facilitate the collection of the total wastes and prevent the loss of nitrogen. Solid handling systems involving scraping would have recovered only about 60% of the nitrogen. Hydraulic removal and utilization of the waste without intermediate storage could achieve close to 90% recovery of the nitrogen in the wastewater.

Nitrogen was found in three main fractions of the waste: the large settleable fiber solids; particulate suspended matter; and in solution. In the particulate fraction, nitrogen was found in the form of bacterial protein with a good amino acid profile. The soluble nitrogen was mainly in the form of ammonia and some free amino acids, which had to be captured by conversion into usable biomass.

Single-Cell Protein

The main thrust in the resource-recovery studies was production of single-cell protein (SCP) biomass through the cultivation of bacteria, fungi, algae, and *Moina*. Other resource-recovery methods that were studied were land-disposal systems, ensilage, and direct refeeding and pisciculture. Figures 1.8 to 1.11 show the overall system and the actual R&D facilities that were built and operated for a period of 10 years.

Water Recycling

In traditional pig production in the tropics, pig pens are hosed down once a day. The purpose is to cool the pigs and to clean the pen floors and the pigs themselves. The volume of water needed daily ranges from 15 to 45 L/SPP. Traditionally, the water is collected in shallow wells or ponds, most

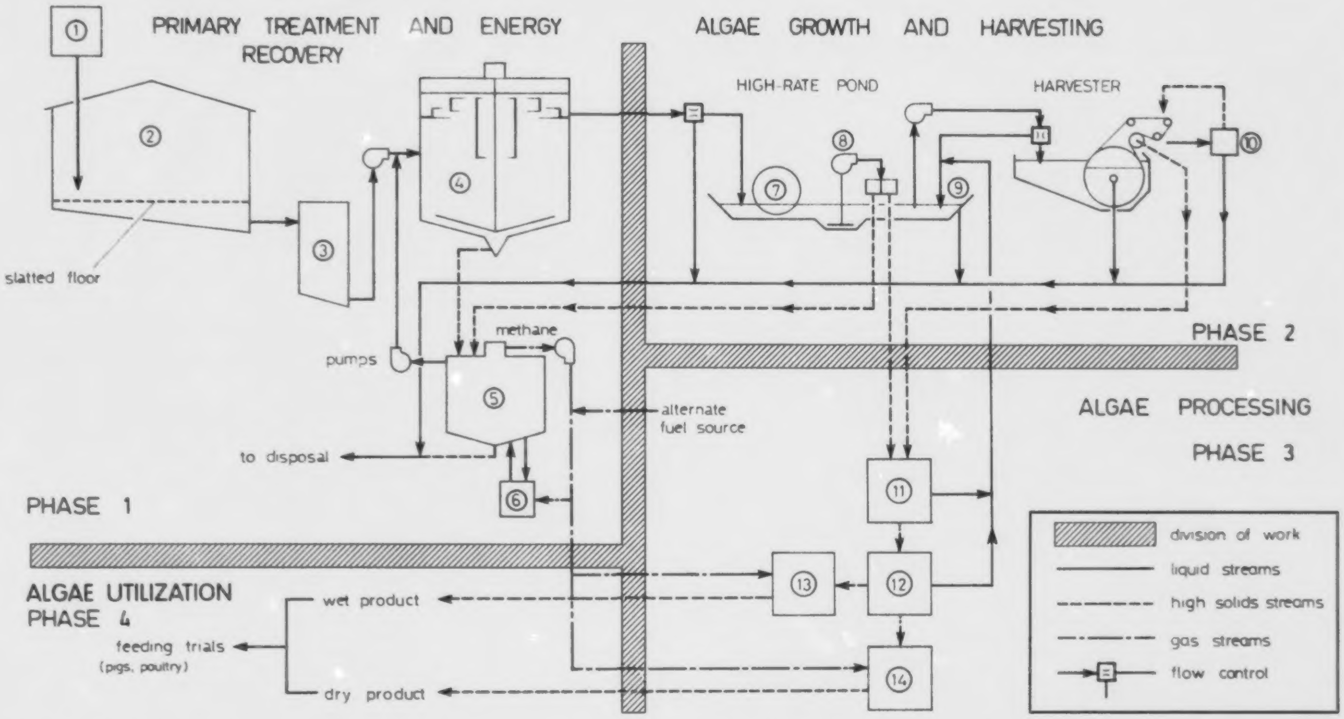

①
PRIMARY TREATMENT AND ENERGY RECOVERY
ALGAE GROWTH AND HARVESTING
HIGH-RATE POND
HARVESTER
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
⑬
⑭
slatted floor
pumps
methane
alternate fuel source
to disposal
PHASE 1
PHASE 2
ALGAE PROCESSING
PHASE 3
ALGAE UTILIZATION
PHASE 4
wet product
dry product
feeding trials
(pigs, poultry)
division of work
liquid streams
high solids streams
gas streams
flow control

Fig. 1.8. The high-rate algae pond total recycle system: 1, flushing water; 2, pig confinement; 3, sump; 4, sedimentation tank; 5, anaerobic digester; 6, digester heater; 7, paddle wheel mixer; 8, excess solids remover; 9, overflow weir; 10, precoat processing; 11, thickening unit; 12, dewatering plant; 13, heat pasteurizer; 14, drying unit.

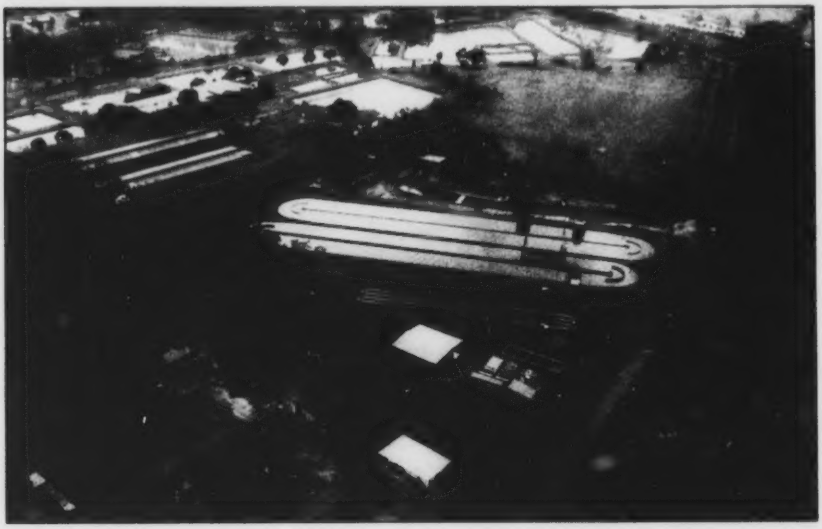


Fig. 1.9. The total recycle system in May 1985, as seen from the southwest corner of PPRTI. The barns in the foreground were built in 1974 with slatted floors and deep pits. Subsequently, two barns were modified to create oxidation ditches beneath the slatted floors to study cultivation and refeeding of bacterial SCP biomass. The major components of the total recycle system were the two homogenization tanks in the foreground, the four sedimentation tanks, the biogas digester on the right, the four pilot and two demonstration size high-rate algae ponds, the harvesting building, and the sand filter beds. The two narrow pig barns (top left) were built with flushing systems and a collection sump from where wastewater was pumped to the homogenization tanks. The overflow from the algae ponds flowed by gravity to the flushing tanks of the barns. The concrete pond above and to the right these barns received the overflow and recycled water. The other ponds at the top of the photo are fish ponds.

of which are fed by surface runoff. However, in intensive pig farming, where land may be limited to as little as 5 m^2/SPP, catchment of rainwater from the farm alone can never meet water requirements. Therefore, water must be recyled and reused.

Water-recycle systems were tested at PPRTI and at the Ponggol Pigwaste Plant. As indicated in Figs 1.7 and 1.8, one of the end products of the treatment processes was water, which was recycled after algae were harvested or bacterial cells were separated. A system designed for automatic recycle of treated wastewater on an individual farm was designed for a 35 000-SPP industrial farm (Fig. 1.12). In this system, automatic siphon tanks were placed at the end of each long barn (Fig. 1.13). When filled, the siphon tanks released large quantities of water that flushed the waste from the pig pens and conveyed it into the aerated anaerobic lagoon. Effluent from the clarified lagoon was then pumped up to fill the siphon tanks.

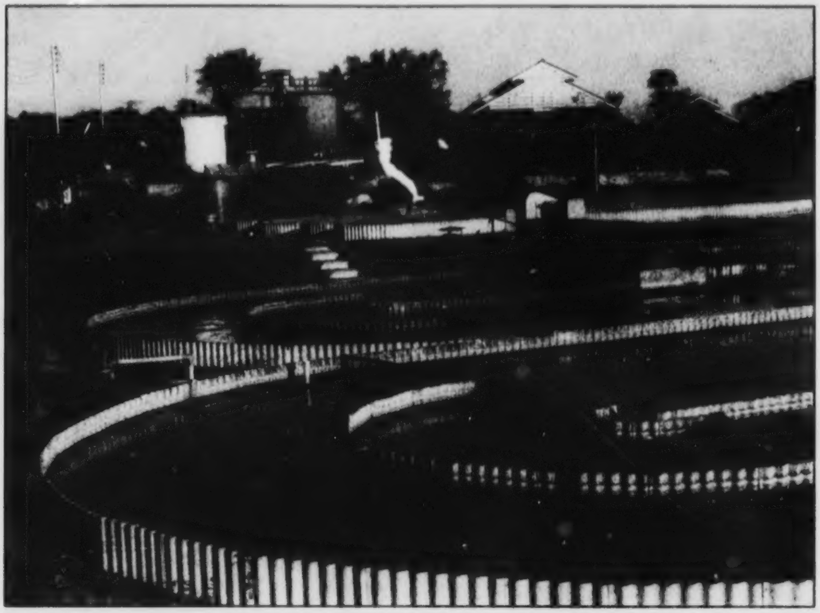


Fig. 1.10. The total recycle system at PPRTI, as seen from the east, showing two demonstration ponds in the foreground (note the corrugated side walls, the four pilot ponds in the next level, the two homogenization tanks, the four sedimentation tanks, the 15-m^3 high-rate digester on the left, and the 50 cubic meter neoprene biogas storage bag on the right in the top terrace level.

Solids Disposal

No matter how extensive the treatment of animal wastewaters, there are always solids left for final disposal. That is why the waste-control requirements (see Table 1.2) included both solids stabilization and liquid treatment. Solids stabilized by anaerobic digestion to reduce their organic content to 70% TVS/TTS, and dewatered to 20% TTS (80% moisture), can be stored for a long period, transported easily, applied to land or used as landfill, readily dehydrated, or incinerated if necessary.

The dewatered solids from pilot plants were disposed around fruit and ornamental trees. Experiments were conducted on the dried solids from the sand filter beds of the Ponggol Pigwaste Plant to determine their compostability without the addition of sawdust. Although the carbon to nitrogen ratio was about 12, thermophylic temperatures could be reached in windrow composting piles. The dried solids could be stored in the open and landfilled without any special problems.

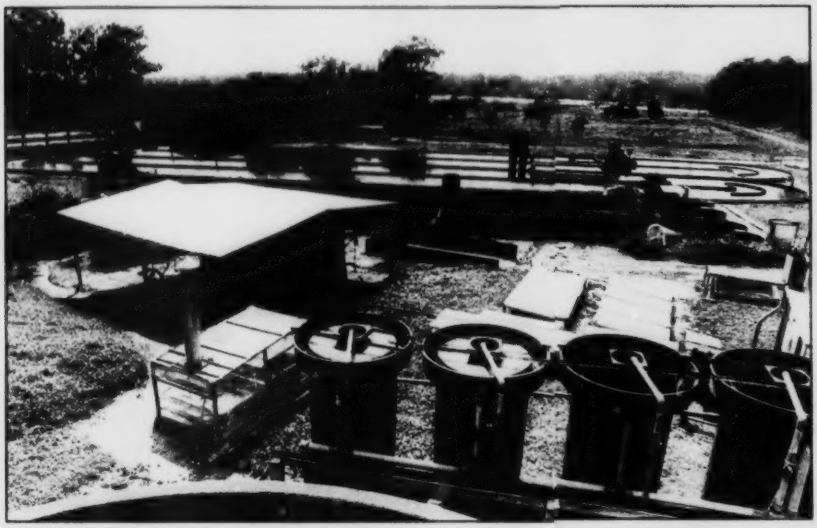


Fig. 1.11. The high-rate algae pond system as seen from the top of the homogenizing tanks overlooking the four fiberglass sedimentation tanks. Immediately below the last tank on the left is a solar drier, whose drying of algae was supplemented with the heat from the burning of biogas stored in the neoprene bag under the shed. The solar heat exchanger is between the biogas digester (not shown on the right) and the biogas storage bag on the left. A small, sludge-drying sand filter bed is shown (centre right) covered with a plastic transparent sheet; the gravel is being laid for another larger filter bed in the centre of the picture. Note the three sedimentation tanks, next to the pilot and demonstration ponds, that were used to thicken solids removed from the depressed section of the high-rate algae ponds. At the top left is the algae harvesting and processing building (reproduced with permission of The Straits Times Press).

Farm-Scale Waste Recycling Plants

The R&D efforts culminated in the development of waste resource recovery and recycle biotechnologies that had been tested under experimental field conditions and showed promise. It remained for their viability to be demonstrated on large, field-scale plants.

Three major treatment plants were developed and tested over several years of operations at three sites:

- an algae recycle system for a standing pig population of 1 500 pigs at PPRTI from 1978 onward;
- a lagoon treatment system on a private farm of 2 500 SPP from 1978 to 1983; and
- the Ponggol Pigwaste Plant on the 35 000 SPP Industrial Farm in the Ponggol Phase III PFA from 1985 onward.

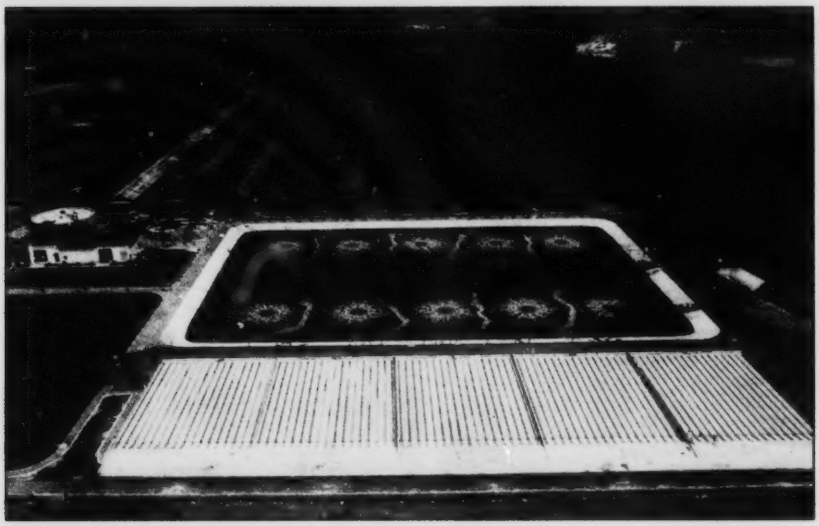


Fig. 1.12. The Ponggol Pigwaste Plant (PPP) as seen from the east looking at the five sludge-drying sand filter beds and the anaerobic lagoon with all 10 aerators in operation. The concrete outfall of the lagoon is on the right. The two jettys in the lagoon were for the overflow pipe and the crane was used to remove the aerators for servicing. The eight Phase II barns were built on a 1% slope with an interceptor drain at the near end. At 285 m, these barns were the longest in the world with automatic flushing. The three wide barns on the right were for farrowing, dry sows, and weaner pens. The five narrow barns were for growers and porkers. The photo shows the primary sedimentation tank, the 1 500-m^3 digester, and the aboveground oxidation ditches (also see Fig. 10.4). The building with the two large doors (centre left) housed the boiler/heat exchanger, the chemical/polymer dosing tanks and associated equipment, the decanting centrifuge, the generator-set running on biogas, and the electrical control room. The recycle pond for treated water is in front of this building.

These plants were built with sufficient flexibility to allow experimentation with individual unit processes.

The unit treatment processes demonstrated in the Ponggol Pigwaste Plant were grouped into three modules of treatment:

- solids stabilization treatment (SST), which constituted primary treatment;
- most practical treatment (MPT), which was secondary treatment used in areas where odour control was critical and 95% reduction in BOD_5 was required; and
- best demonstrated treatment (BDT), a tertiary treatment used for 99% reduction in BOD_5 and total recycling of treated liquid, solids, and energy recovery.

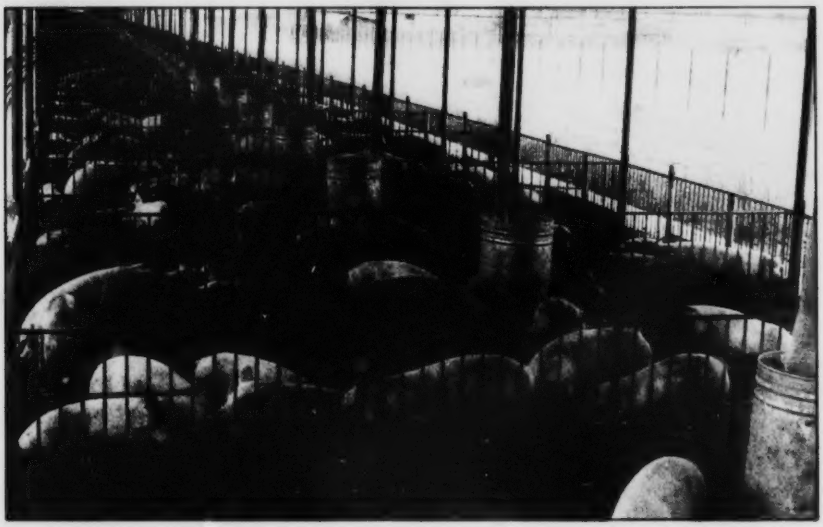


Fig. 1.13. New porker barn design adopted in 1979 for the large commercial farms of Ponggol PFA Phase III. The design offered automatic flushing and removal of wastes to minimize malodour production, as well as good ventilation. Pigs were still hosed with water for cooling but not as often as in wide, concrete-floor barns.

The most economical treatment technology (MET) was between MPT and BDT. It met strict liquid effluent standards, but did not include energy recovery through digestion.

This book focuses on the performance of these unit processes. In other parts of the world, appropriate combinations of these processes can provide the desired treatment.

Studies on Malodours

An important part of waste management is odour control. In May 1977, relocated pigs began to arrive in the Jalan Kayu area of Phase II PFA. In October 1977, residents of the housing estate across the road lodged complaints about pig odours. Interestingly enough, several farms with an SPP of 12 500 had been in existence in the area for over 20 years. The SPP had increased by only 1 000 SPP when the complaints began. However, the new farms could be seen easily from the road, whereas the old farms were out of sight. This led to the planting of fast-growing shrubs and trees along the full length of roads bordering the PFA. Trees were also planted in a 300-m buffer zone between the farms and the residential areas.

A task force studied the problem for a year. They identified the sources of odour, measured the odours, and determined the frequency of emission and distance of travel.

Odour Sources

A limited survey of farms indicated that cesspits were a source of strong odours; therefore, work was continued on better methods of cesspit operation, and a cesspit deodorant was field tested.

Surveys of odours over several weeks indicated that the PFA was not a single massive source, but that the odours could be traced to two individual farms whose husbandry practices generated malodours. The sanitation practices of these farms were surveyed by the task force and improvements were recommended. After implementation of the new practices, the odour emissions were measured again. However, it was not possible to make many improvements because of the limits imposed by building design. Project engineers came up with ideas for future buildings, which were tested at two private farms.

Odour Measurement

The first gas used as an index of pig waste odour was hydrogen sulfide (H_2S). At first, it was measured with papers impregnated with lead acetate. Later, strips that had been precalibrated and tube vials attached to calibrated suction pumps were used. Extensive studies were conducted in and out of pig pens, in and around the farms, and inside the residential estates. H_2S-measuring strips were useful for the detection of pig waste smell, but were not reliable in giving a clear picture of the intensity of pig farm odour.

Odour intensity and distance of travel were also measured organoleptically by task force members who carried out 24-h sampling of the entire area to detect odours. These surveys were used to plot odour travel.

Odour panels were established. To ensure objectivity, the pig farm odours were captured on cotton flannel swatches exposed to specific sources on the farm for several hours and then brought to the laboratories at PPRTI to be smelled and compared by panel members. Over 50 people participated on the odour panels.

Ammonia measurements with tube vials were used as an index of malodours, particularly for studies to determine the deodorizing effect of enzymatic additives that were being promoted by several companies. Threshold odour levels were determined organoleptically with two mechanical devices: the "scentometer" and a direct-reading "olfactometer." Both devices and the results of all studies are described in the section on malodours.

Frequency of Emission

Malodours were most frequently emitted from two farms with particularly poor sanitation. The majority of the odours in the PFA came in "malodour puffs" that lasted 1 to 15 min. The presence of strong pig odours in the adjacent residential estate made it unlikely that the residents would adapt to the odour as a normal part of the environment. Blanketing malodours occurred quite regularly on calm humid nights throughout the PFA and within a 300-m radius of the farms. The government ceased allocating lots for new pig farms in this PFA in late 1978. All pig farms in Phase II were phased out in 1986.

Conclusions

Two of the recommendations of the task force on malodours in 1979 were

- In choosing a site for a new pig estate, geography and microclimate must be studied carefully to minimize problems of odour travel and visual appearance, which is also important for good public relations.
- The slatted-floor, flushing gutter system is effective in reducing odour problems.

These recommendations were incorporated in the design and development of Phase III of the Ponggol PFA from 1981 to 1983.

Change of Pig Farming Policy

In 1984, the Ministry of the Environment increased from 300 to 1 000 m the buffer distance between the boundaries of residential housing estates and potential sources of malodours such as sewage-treatment works, incinerators, garbage landfills, and PFAs. "Malodour puffs" from the PFA could travel as far as 900 m.

In 1984, the Deputy Prime Minister of Singapore was placed in charge of the Primary Production Department to once more review livestock production policies. The Minister decided that Singapore would no longer need to be self-sufficient in pork, eggs, and poultry, because the limited land and water resources should be used for human housing and factories. The Minister also announced that the time schedule for carrying out the government's policy of completely phasing out pig farming from Singapore would be accelerated and that the new target date would be 1987 instead of 1995.

Regional Training Program

In view of this change in policy, an intensive effort was made to run as many experiments as possible in the two demonstration plants so that their performance could be recorded for use elsewhere. A regional "hands-on" research training program was funded by Canada's International Development Research Centre (IDRC) through which about 44 engineers and scientists from countries within ASEAN, as well as Korea and Mexico, spent 2 months in Singapore carrying out miniprojects using the two demonstration plants. The reports written by these trainees have been incorporated in this book.

Through technical exchange programs in the spirit of Technical Cooperation among Developing Countries (TCDC), an effort was made to transfer the Singapore experience on PFA to Malaysia, which faces similar problems. Over 10 engineers, veterinarians, and scientists from Malaysia spent time in Singapore surveying major aspects of intensive pig farming, studying policy-implementation documents, and operating treatment plants. This book refers to major publications that were generated while trying to apply the Singapore experience in Malaysia.

Questions and Answers

Government Policies

The sudden change in national policy and the acceleration of phasing out of pig farming in Singapore shows the vulnerability of pollutive industries and, particularly, livestock production, whose malodour and water pollution potential are no longer tolerated by the public or by politicians.

Most of the questions posed here are representative of questions posed in Parliament by the Minister and, as such, reflect the kind of criteria that will be used in other countries to control pig farming, in particular, and the livestock industry, in general.

Question 1. Could it be that limits on the import of live pigs, ostensibly for health reasons, actually maintained high domestic prices that made commercial farming viable?

Answer 1. Regulation of the import of live animals, and particularly pigs, is practiced by all countries, both for health reasons and to regulate meat prices. Such regulations normally reflect national food security policies and political realities. In many countries where the lobbying power and the political influence of the pig farming industry is substantial, import restrictions are severe, even in countries with liberal trading policies. The farming community did not have a strong political lobby and, by 1979, Singapore had established a free-trade policy in all sectors and was aggressively opposing the protectionist policies of other countries. It was politically more palatable to remove an industry that might be perceived as protectionist than to justify pig farming as a food security matter.

The 62 farmers in Singapore who decided to incorporate in 1981 and to go into commercial pig farming until 1995 did so knowing that the import of live pigs would no longer be controlled to the degree it had been. In 1981, the import of pigs was liberalized because the allocation of land for pig farming was such that only 60% of the national demand could be met by local production. Pig farming had been profitable in the 1970s, and the farmers had obviously calculated that it would continue to be so, otherwise they would not have invested such large amounts of money on the premise that their profits would be ensured by strict pig import policies.

Question 2. Would it be cheaper to import all pork requirements than to clean up the pollution produced by pigs reared in Singapore?

Answer 2. The question presumes that in the exporting countries pigs would be raised without pollution controls, or that environmental controls in such countries would be sufficiently cheap to pay for the additional costs of handling and transporting pigs to Singapore. All countries can be expected to impose environmental limits that would add to the cost of production, but supplying countries might be willing to subsidize their environmental cost for the production of pigs for export.

In all neighboring countries, pig production practices were similar to those in Singapore, causing equivalent water pollution. However, these countries were not as limited in land and water resources as Singapore. Because they had agriculture-based economies, neighbouring countries were more prepared to delay taking firm stands on animal pollution than was highly urbanized Singapore.

The Government of Singapore did embark on a major campaign to get the people to use frozen pork. Chinese prefer what is called "hot pork" (i.e., fresh meat); pigs were slaughtered at night and delivered to the market by dawn; by noon, all the meat was marketed. Such traditional habits would require a long time to change unless there were compelling economic reasons. It is also important to note that the countries of northern Europe, who are the major exporters of processed pig meats, are also in the forefront of environmental protection legislation.

The cost of the pollution control measures proposed for the pig farms in Singapore increased the cost of meat by less than 4%. These costs could be absorbed by the farmers.

Pig production in Singapore was competitive with neighbouring countries. Thailand, a country that was a major exporter of corn and other grains and had a long a tradition in pig production, could not compete with local Singapore pig production costs, if the additional costs of handling and transporting live pigs by ship more than 1 000 km were included. Land transportation in truck trailers would have made Thai pigs competitive, but such transport was not politically possible because the trucks would have had to travel through Malaysia, a country with its own pig production geared for export to Singapore. Moreover, it would have been politically difficult for Malaysia to permit the transport of pigs through villages and towns where the majority of the people were Muslim.

Question 3. Is it wise to spend millions of dollars to get the BOD_5 to 250 ppm, which is equivalent to the BOD_5 concentration of raw sewage?

Answer 3. Effluent standards set in terms of biochemical oxygen demand (BOD) do not portray the full picture. Mass emission rates also need to be specified. In this case, where only 20 L of wastewater were generated per pig per day, a BOD_5 of 250 mg/L amounted to a discharge of 5 g BOD. On the other hand, sewage with a BOD_5 of 250 mg/L would contain 50 g BOD, or 10 times that of pig wastewater, because the average person generates 200 L of wastewater every day. If pig wastewater was diluted by 200 L per pig rather than 20 L, then the BOD_5 of the wastewater would be only 25 mg/L.

Moreover, in setting standards, it is also important to consider the percentage of pollutant reduction. Treating sewage from 250 to 25 ppm amounts to a 90% reduction; going from 5 000 to 250 mg/L BOD_5 in pig wastewaters represents a 95% reduction in pollution.

Furthermore, as was emphasized in the development of the waste-control regulations (see Table 1.2), it is important that the issue of solids be addressed adequately, not just the liquid discharge. Firms that tried to market pollution-control equipment could meet the liquid effluent standard, but had difficulty meeting the standards for solids treatment.

Raw sewage of 250 mg/L BOD_5 has settleable solids that turn into putriscible bottom sludges and add to the intrinsic malodours of raw waste. Treated pig wastewater of 250 mg/L BOD_5 will contain only 5% of the original suspended solids and should not smell. All these conditions are stated in Table 1.2. BOD is only one of the conditions to be met by the treatment process.

Question 4. Because farms will have to cease rearing pigs by 1995, would it not be better for farmers to quit earlier rather than waiting until 1995?

Answer 4. The farmers who decided to incorporate and accept the provisions of the pollution-control regulations did so of their own free will. Therefore, it can be assumed that they had calculated the potential returns on their investments. The farmers, and those who loaned the money for the new farms, were apparently satisfied that they could get their money back. However, one cannot dismiss the likelihood of failure. The livestock industry is vulnerable to many uncontrollable factors such as changing grain prices, weather, consumer trends, and the world economy. From 1985 to 1987, pig prices plummeted to their lowest ever levels, but began to rise in 1988. Therefore, it is conceivable that farmers would have sought government approval to extend their stay beyond 1995, if they could not recover their total investment and make a decent living.

Question 5. Were the rental rates charged to farmers lower than those for other economic sectors and, therefore, a form of subsidy?

Answer 5. The annual rental rates for the commercial farms were 2 830 USD/ha. The rate was based on full recovery within 14 years of the total government costs in developing the site for pig farming. The land-development costs included resettling squatters, clearing the area, land forming, establishing a utilities network, constructing roads, and landscaping. The same site was to be developed into housing after 1995, but occupancy was not planned before the year 2000; the use of the site as a PFA was not considered detrimental to the intended future use of the land.

The annual rental rate of 2 830 USD/ha could be absorbed in the cost of production. It amounted to less than 1 USD/PMY (porker marketed per year), based on 3 200 porkers being produced per year from the 2 000 SPP/ha of commercial farms. This cost translated into about 0.01 USD/kg of pig.

On the other hand, the same infrastructural facilities of the area could have been used for factories at higher rental rates. In this case, one has to consider whether food security is a critical issue. In other words, could the country obtain the pork it needed as easily and as readily as manufactured goods? In the 1970s, the answer was definitely no, but political and economic conditions changed drastically in the 1980s.

Question 6. Could resources that were scarce in Singapore, such as water, be allowed to be used for pigs?

Answer 6. Because farms were allowed only 5 m^2/SPP and there were no deep underground aquifers to be tapped, pig farms could not be self-sufficient in water. Public water supplies were used by the majority of the large commercial farmers for drinking. Daily, this amounted to less than 10 L/SPP. On the other hand, Singapore depended on Malaysia for more than 60% of its water supply. Therefore, water was a major factor, particularly when combined with the scarcity of land.

Question 7. Could pig farming remain economically viable after paying the full costs of pollution controls?

Answer 7. There is no question that the farms could have remained commercially profitable for a decade or more and still have achieved a 90–95% reduction in pollution. The second and third phases of pollution control, which would have required reductions of 98–99%, would have cost twice as much as the reduction to 90%. Such levels of treatment would have introduced new dimensions into pig farming: the management of mechanical equipment, with its inherent propensity to break down at critical times, and the husbandry of microbes and biological processes. These new requirements would have required formally educated people with specialized training. The small farms could not have afforded this unless cooperatives were formed to manage centralized systems.

A major handicap in Singapore was the lack of land for the disposal of solids. Solids had to be disposed of in landfill sites, which was expensive because of the disposal fees and the cost of transportation. Also, this meant that the solids had to be dewatered to at least 20% dry matter so that they could be transported and disposed. Unfortunately, because of religious sensitivities, even composted solids could not be used in public parks, and Muslim labourers refused to handle the compost. The only practical alternative was to use the solids as a mulch for trees.

Question 8. In land-scarce Singapore, would pig farms have to be located too close to densely populated areas?

Answer 8. Pig farm malodours accelerated the phasing out of pig farms in Phase II PFA because the farms were within 300 m of residential areas. By 1984, a new housing development was completed in an area that was less than 1 000 m from the Ponggol Phase I PFA. In the meantime, the Ministry of the Environment had decreed that sewage works, landfills, incinerators, pig farms, and other plants that might emit objectionable odours could not be located closer than 1 km from a residential housing area.

In 1985 and 1986, the Ministry of the Environment measured the hydrogen sulfide concentrations within the Hougang New Town, a community of several hundred thousand people. It was apparent that hydrogen sulfide had reached irritating levels. The resulting malodours were attributed to the Phase I Ponggol PFA whose boundaries were within 1 000 m of the residential area.

The Government of Singapore decided to accelerate the phasing out of pig farming by 1987 instead of 1995; the actual phasing out could not be completed before 1990. All the farmers were compensated for their investments and the engineering companies that completed or began the construction of plants were given compensation to cover their actual expenses.

(It should be noted that the Minister who was assigned the task of reviewing and modifying the livestock policies of the country was an economist by profession who had been in politics for several decades and had served as Minister of Education, of Defence, of Finance, of National Development, and in many other capacities. As such, he was eminently qualified to consider these basic issues of food security, domestic animal production, etc., in terms of their economic and political implications for Singapore.)

Technology Transfer

Question 9. It was not feasible to transfer technologies of pig waste treatment used in colder climates to the tropical conditions of Singapore. Can the technologies developed and tested in Singapore be transferred to other places, and can these facilities be used for other types of organic wastes?

Answer 9. Farmers in Singapore used water to wash and cool the pigs and to clean the pens. The resulting wastewater contained about 1% solids and was therefore too dilute to be handled and treated as a slurry. Yet, the wastewater was not as dilute as human sewage. Therefore, technologies that were suited for slurries or for dilute sewage could not be directly applied. The average mean water temperature of 28°C made it possible to design smaller treatment vessels because less hydraulic detention time was required compared with cold climates. One company insisted on demonstrating a thermophylic digester that had been successful in northern Europe, but the company abandoned the idea of a heated digester after a few months of operation.

An attempt was made to rear pigs without using water, as was being tried in other countries with colder climates. Pigs were reared on sawdust litter that absorbed the urine and feces. The litter temperatures rose several degrees above the temperature of the traditional concrete floor. Pigs became restless and uncomfortable. Their performance in terms of daily gain and conversion efficiencies suffered.

The best thing that can be transferred is the experience accumulated over the years in Singapore. Although pig production in neighbouring countries was similar to that being practiced in Singapore, land constraints and pressures from the urban sector for malodour control were not the same. Therefore, arrangements were made for engineers and scientists from those countries to come to Singapore for a few months to operate the various facilities and to gain experience in the performance and problems of various treatment biotechnologies. Treatment technologies do involve complex equipment, but their success depends on the viability of the microbiological processes. These can best be managed by people who understand the fundamental principles and have hands-on operational experience.

The Ponggol Pigwaste Plant was given to the National University of Singapore to study the performance of the various treatment processes for different types of wastes. The civil and mechanical works were designed with such flexibility.

Waste Resource Recovery

Question 10. Can resource recovery from pig wastes pay for itself?

Answer 10. This and other questions are answered in the technical chapters that follow. Pig farming integrated with waste resource recovery and recycling is an ancient traditional practice in the Orient. It is still practiced on small farms that have a few pigs and adequate land. As farms increase in size and lose their access to cropland, it is imperative that the art of recycling be developed into a new and practical science and technology that can be designed for the needs of pig farming areas anywhere in the world. This purpose was pursued during the past decade in Singapore. It is the purpose of this book to pass on that

Singapore experience to stimulate the development of resource recovery and recycling biotechnologies.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Role, trends, importance, supply, and demand of pig production at the local, regional, and national levels.
2. Environmental policies, relevant legislation, effluent quality standards, mass emission rates, monitoring parameters, and energy and other resource limitations for livestock production.
3. Technology standards, criteria for selection, transfer of technology and experience, identification of research and development needs, and assessment of technical feasibility.
4. Resource recovery: existing practices, conservation needs and ethics, and technological–environmental–economic impact.
5. Political considerations: social constraints, sources of funding, farmer interest and support, trade implications, and public tolerance.

Chapter 2

Pig Production

This short chapter was written mainly to introduce the terminologies of pig rearing and pig production practices, with particular emphasis on tropical pig production. As such, it is laconic and touches only on major aspects of pig rearing. However, it is important that the concepts and principles of this chapter are understood.

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Pig Production Cycle

The life cycle begins with the piglets, which normally weigh 1.5–2 kg. In each birth event (farrowing), 8 to 12 piglets are born, although sows can produce litters of more than 20. Large litters have many small piglets, most of which may not survive; those that do may grow very slowly.

The piglets remain with their mother for 21 to 42 days, depending on the pig management practice of the farm. Piglets are weaned by removing the sow from the pen. Thereafter, they are fed formulated feed. After a few days of adjustment, the weaned pigs are kept in weaner pens for an additional 30 to 60 days until their weight reaches 20 kg. They are then moved into porker pens where they remain until they reach their market weight of 75–100 kg. The life span of a porker is anywhere from 150 to 230 days from birth to the abattoir. When slaughtered, the dress weight of the porkers is approximately 70% of live weight.

The main inputs in pig production are: breeding stock (gilts, sows, and boars); water for drinking and cleaning; feed (grains, protein supplements, minerals, and vitamins); preventive medicines and therapeutic drugs; housing and materials handling; management and husbandry; and sanitation, disinfection, and waste removal. Waste removal must be integrated with proper disposal in the environment, which means pollution control, resource recovery, and recycling. The pig production cycle can be divided into three phases: breeding, weaning, and growing/finishing.

Breeding

Breeding involves the mating of a sow or gilt (a female pig 5–7 months old that has not been bred before) with a boar, or artificial insemination. After conception, there is a gestation period averaging 114 days, during which the pregnant sows are housed in individual gestation pens.

A week before the sow is scheduled to deliver, she is moved into an individual farrowing pen. During the farrowing period, the animal requires special care and attention. The period from birth to weaning is called the lactation period. After the piglets are weaned, some of the best female weaners are kept as replacements for the sows. These animals constitute the herd of gilts.

Mating Period

The mating period lasts from the date of weaning the previous litter until the day of conception. During this time, the sow must be kept in a pen or a stall close to boars to stimulate estrus. Estrus is the cyclic period of sexual activity in female mammals. It is commonly called "heat" and is characterized by secretions, ovulation, and acceptance of the male.

The timing of the sow's first estrus after weaning varies from 5 to 40 days. The conception rate for first service is normally about 80%. The estrus cycle of the sow is 21 days. In commercial pig production, it is desirable to reduce the number of days between farrowing and conception to produce more litters per sow per year. A high proportion of the sows that are in good physical condition will begin to come into heat 3–7 days postweaning. Adequate boar power is essential for effective synchronization of postweaning heat.

If a sow fails to conceive within 28 days postweaning, the farmer will cull her. This is enough time for her to have been bred twice. With each 21-day delay, the sow must produce two extra pigs just to pay for the time and feed she has consumed. Similarly, if gilts do not conceive after being bred three times, they are culled.

Gestation Period

The gestation period ranges from 110 to 120 days; 114 days is the average. During this period, the sow should be individually confined to prevent fighting with other sows and to restrict her activity and feed consumption. Individual stalls, rather than pens, are recommended to reduce embryo loss as a result of fighting. These gestation stalls may be the same ones occupied by the sow during breeding, or they may be located in another part of the barn. If there are separate facilities for breeding and gestating sows, then extra movement of animals is required. The choice of combined or separate breeding and gestation areas should be made by the manager when the farm is being designed.

Lactation Period

The lactation or suckling period of the sow begins when she farrows (i.e., gives birth to her litter of piglets); it ranges from 3 to 5 weeks. A long suckling period is not practiced in commercial production for economic and productivity reasons. Farrowing pens are the most expensive units to construct and, as such, need to be reused as often as possible. The nursing of large piglets weakens the sows, and thus affects their productivity and rebreeding.

Gilt Replacements

Immediately following the lactation period, old and unproductive sows are culled. These sows are replaced by young gilts. The number of gilts kept for breeding must be sufficient to replace those culled. Because the first estrus cycle of gilts is variable, it is recommended that one gilt be kept for every three or four litters farrowed. A gilt is considered a "replacement" gilt from the time her litter mates are sold for slaughter until she is bred at about 8 months of age. Replacement gilts may be housed in group pens or in stalls in the breeding barn. In either case, they are placed near boar pens to stimulate sexual development.

Most gilts reach puberty at 5–6 months. From this period on, the gilts will periodically show signs of "heat" (i.e., will stand to be mated to a boar). The estrus cycle will stop temporarily when the gilt is pregnant and start again after the sow has been weaned from her piglets. It is best not to mate the gilt in her first two heats. During these two heats, only a small number of eggs (ova) are produced; therefore mating would result in only a small litter. Moreover, at this stage, the gilt is still small and growing. Pregnancy might overly stress the animal, interrupt her growth, and result in difficulties in rearing the litter.

Weaning

When the suckling period is ended by removing the sow from the farrow pen, the piglets are called weaners. The demarcation between the weaner period and the grower/finisher period depends on the day of change in ration. Generally, piglets are called weaners until they reach 20 kg live weight at about 8 weeks of age.

It is customary to wean pigs from 3 to 5 weeks of age. If pigs are weaned at 3 weeks or younger they should weigh a minimum of 5 kg. Some reasons for seeking early weaning are to produce more than two litters per year from each sow; to take advantage of the high feed-conversion efficiency in young piglets; to produce heavier and more uniform grower pigs; to save on feed for sows because of the short lactation period; and to improve the welfare of the sow, which is neither overly stressed nor loses weight excessively during the short lactation periods. A survey in 1986 of the 10 largest commercial farms in Singapore showed that the mean weaning age was 27 days and the range was 20–30 days.

The period after weaning is the most stressful on the young piglets as they are taken away from the sow and forced to change from a milk diet to dry feed. Often, they are also moved to a new pen. The stress of feed change is lessened by starting the baby pigs on a prestarter dry feed while they are still nursing and by continuing them on the same diet for at least 1 week before changing to the starter ration.

Most managers move the piglets from the farrowing stall to weaner pens on the day of weaning. Some producers arrange the production schedule so the piglets can remain in the farrowing stall 3–7 days after weaning to further reduce stress. If this practice is to be used, then it must be considered in the planning phase of farm development because more farrowing stalls will be required. The disadvantage of this scheme is the additional cost for farrowing stalls and the extra space they require.

Feed for weaner pigs is normally a dry mash. Weaner pigs consume a daily maximum of 0.7 kg dry feed. On large farms, mechanical conveyors can be used to move the feed to pen self-feeders.

The weaner pigs are 8–10 weeks old when they are moved to the grower pen. After the pigs are moved out, the weaner pen should be thoroughly cleaned and left to rest for 3 or 4 days before a new batch is moved in.

Growing and Finishing (Porkers)

In commercial production, the last phase may be divided into the grower (up to 55 kg of animal live weight) and finisher stages (up to market weight). Growers are fed a ration that is high in protein; whereas fibre content is increased in the porker ration. Because growers are smaller than porkers, they require less space per pig and thus, there are economic savings in having two types of pens, but this means moving the pigs twice.

In Singapore, the average market age was 200 days (28 weeks), at which time the pigs weighed 80 kg. Some farmers used superior genetic strains and good management to produce market pigs in 170 days (24 weeks).

Types of Farms

Closed Herd

The majority of the farms in Singapore were "closed herd." Breeding stock was replaced by gilts from the farm itself. A few of the boars were kept for breeding. High-performance boars and progeny stock that were certified disease-free were introduced into the farm to enhance productivity by cross breeding. All references to pig farms in this book refer to closed-herd farms.

Weaner Producers

Weaner-producing farms keep breeding stock and sell weaners to other farms for finishing/fattening. These farms are more typical of cooperative farms and may be combined with purebred production. There was a very small number of such farms in Singapore.

Fattening Farms

Fattening farms buy weaners for fattening. They do not keep any breeding stock. These farms are more typical of cooperative arrangements. No such farms operated in Singapore.

Because of the fluidity of the pig market, many of the farms did not maintain a fixed type of production. Rather, they changed with market demands, e.g., when there was insufficient demand for suckling pigs, farmers kept them longer and later sold them as weaners or porkers.

Productivity Parameters

Table 2.1 shows major sow productivity parameters. The table includes the levels that are considered minimal for viable commercial production and the levels achieved by the small and commercial farmers in Singapore in 1982 and 1985. Farm productivity is measured as the total number of porkers marketed per year (PMY). Because age and weight of market pigs vary, a more accurate production indicator is the weight of pig carcasses produced per year per sow, but the latter is not useful in the design of pig housing and waste-management systems. Engineering production parameters that are useful are standing pig population (SPP) and standing pig marketed (SPM) per year, which may include piglets sold for roasting

Table 2.1. Sow productivity in small and large farms in Singapore.[a]

Sow productivity parameter	Min.	Problem	Small farms 1982	Small farms 1985	Large farms 1982	Large farms 1985
Farrowing index (litters per sow per year)	2.1	2.0	1.7	2.2	1.9	2.4
Litter size at birth (no. of piglets)	9.3	9.2	9.4	10.6	9.0	9.7
Litter size born alive (no. of piglets)	9.0	8.8	8.5	9.3	8.4	8.9
Stillborn piglets per litter (no.)	0.5	0.7	0.7	1.3	1.0	0.8
Piglets weaned per litter (no.)	7.9	7.5	7.8	6.8	7.1	8.1
Weaners per sow per year	15.0	15.0	14	18.7	11	19.2
Birth weight (kg)	1.3	1.2	—	—	—	—
Weaning weight (kg)	5.0	5.0	—	—	—	—
Percentage of litters with <7 piglets	20.0	20.0	29	12.9	26.1	17.3
Prewean mortality (%)	10.0	14	28	14.4	10.8	
Weaner mortality (%)	0	3	—	—	—	—

[a] Productivity is measured by the number of pigs produced per year, which is dependent on the weight and age at which the pigs are marketed and other management practices. Litter size and mortality rates, therefore, must be monitored to remedy situations when productivity reaches problem levels. The introduction of record keeping, computerized analysis of data, and other housing and management changes resulted in higher sow productivity in the Singapore pig farms.

(2–3 kg), roasting pigs (35–50 kg), culled sows and boars plus porkers, or PMY.

SPP Parameters

Most animal scientists and veterinarians define the size of a pig farm by the number of sows. This is the standing sow population (SSP). For engineering design of pens of different sizes and waste generation, the population of the various types of pigs and the total number of pigs need to be calculated to produce SPP. Table 2.2 shows the typical distribution of the pig population on a Singapore farm with 100 SPP. A farm with 600 sows (600 SSP), for example, would have 6 000 SPP of which 900 would be piglets (15%), 1 620 weaners (27%), and 2 820 porkers (47%).

Normally, the sow to boar ratio is 25:1 in small farms and 20:1 in large farms. The ratio of SPP to SSP is 10:1 as a rule.

Animal Live Weight

Typical animal live weights (ALWs) of the five major types of pigs are shown in Table 2.2. The mean live weight of the entire farm varies with the weight at which porkers are marketed. On Singapore commercial farms, where porkers were sold at 85–90 kg, the average mean live weight was 54 kg ALW. This is the value used to calculate the amount of waste generated on Singapore farms. In Malaysia, where pigs were marketed at 75–85 kg, the mean live weight on the farms was about 50 kg.

Table 2.2. Typical population distribution in a closed-herd farm and calculation of mean live weight per SPP (50 kg ALW/SPP).[a]

Type of pig	No. in farm (100 SPP)	Mean live weight (kg)	Total live weight (kg)
Sow	10	182	1820
Boar	1	180	180
Piglet	15	4	60
Weaner	27	16	432
Porker	47	53	2491
All	100	50	4983

[a] Most commercial farms in Singapore averaged 54.5 kg live weight per SPP. In Malaysia, the corresponding value was 49 kg/SPP based on actual farms measurements. In farms that keep pigs to 100 kg live weight, the percentage of porkers would be higher. ALW/SPP is used in calculating waste generation.

Pigs Marketed

The number of porkers marketed per year (PMY) divided by SPP is the annual extraction rate. The annual extraction rate in Singapore farms was 1.6 PMY/SPP in the 1970s, but increased in the commercial farms built in the 1980s. For planning purposes, the range that can be used is 1.6–1.9 PMY/SPP.

For a 600-sow farm with an SPP of 6 000 and an extraction rate of 1.67 PMY/SPP, the number of PMY would be 10 000. The total live weight of the PMY at 88 kg ALW would be 880 000 kg of live weight sold per year. At 1.22 USD/kg of live weight (an average sale price in the mid-1980s), the farm's gross income would be more than 1 000 000 USD from the sale of porkers.

Production Parameters

The main production parameters for 10 large commercial pig farms are given in Table 2.3. Cost of production of porkers marketed ranged from 1.05 to 1.28 USD/kg ALW, with the average of 1.12 USD/kg ALW.

Feeds and Feeding

Feed is the most critical input in commercial pig production, representing 74–80% of the cost of porker production. Feeding, which includes the cost of feed plus the costs of labour and materials handling, can be as high as 80–90% of the total production cost. It takes 5 or 6 kg of feed to produce 1 kg of live pork from a closed-herd farm. Prices for live pigs are very sensitive to the price of feed grains.

Table 2.3. Pig production parameters of large commercial farms.[a]

Pig production parameter	Farm surveyed										
	1	2	3	4	5	6	7	8	9	10	Avg.
SSP	1200	1780	400	2100	850	800	2800	1200	1400	500	1300
SPP	12000	17800	4000	21000	8500	8000	28000	12000	14000	5000	13000
Weaning age (days)	28–30	25–28	30	28	25–28	24–30	28	24	25	20–25	26.5
Weaning age (weeks)	4+	3–4	4	3	3–4	3–4	4	3	3	3–4	4
Litter size at weaning (no.)	7.5	8.0	8.0	7.6	7.5*	7.9	7.8	8.2	7.7	8.0	7.9
Farrowing index (litters/SSP per year)	2.0	2.2	2.0	2.1	2.0*	2.2	2.20	2.25	1.9	2.2*	2.1
Porkers marketed/sow (PMY/SSP)	15.0	17.6	16.0	16.0	15.0*	17.4	17.2	18.5	14.6	17.6	16.7
Annual extraction rate (PMY/SPP)	1.5	1.8	1.6	1.6	1.5	1.7	1.7	1.9	1.5	1.8	1.8
Slaughter weight (kg ALW/SPM)	93	86	80	90	80–100	75–95	85	83	85–90	75–100	87
Birth to marketing (days)	195	195–210	195	195	180–210	170–190	187	180	180–210	180–210	204
Birth to marketing (weeks)	28	28–30	28	28	26–30	24–27	27	26	26–30	26–30	29
Cost of production (USD/kg ALW)	1.10	1.05	NG	1.28	NG	1.24–1.10	NG	1.22–1.18	NG	NG	1.12

[a] Data in this table were given by farm managers during a 1986 survey of 10 farms in the Ponggol PFA. NG, not given; *, estimated based on survey data; see list of Acronyms and Abbreviations for other definitions.

Feed Ingredients

Table 2.4 shows the main feed ingredients used in Singapore and the prices paid in 1986. The main ingredients are corn, soybean meal, fish meal, rice bran, wheat pollard, and skim milk powder, most of which are imported in tropical countries like Singapore and Malaysia. Local feed materials that can be used as substitutes for these ingredients are cassava (lack of pigment is a major drawback), palm kernel meal and palm oil sludge (too high in ash and fibre content), sago meal (high bulk), cocoa pods (contain theobromine, which has a bitter taste and is diuretic), and rubber seed meal (not available in sufficient quantities).

Least-Cost Formulations

Because purchase of feed ingredients represents 74–80% of the total production cost, computerized formulations are used to develop least-cost feed rations that are balanced in terms of energy levels, protein content, minerals, and vitamins. Tables 2.5 and 2.6 show the feed formulations and the analysis of grab samples of the six types of rations prepared on commercial farms. The average cost of feed for all rations was 0.18 USD/kg in 1986.

Table 2.4. Changes in the content of feed formulations used on Singapore pig farms in 1950 and 1986, and prices in 1986.

Ingredient	Content in diet (%)		1986 price (USD/t)
	1950	1986	
Maize (corn)	—	30–55	100–125
Wheat	—	—	152
Wheat pollard	—	5–6	110–115
Wheat bran	9.8	10–14	110–115
Fish meal	1.0	3–9	410–460
Meat meal	—	4	300
Soybean meal	—	12–30	205–225
Water hyacinth	12.0	—	—
Skimmed milk powder	—	10–12	900–1045
Copra meal	26.0	0–3	105
Leaf meal	—	3–6	128–148
Rice bran	25.6	5–18	65–115
Cod liver oil	—	2	850–902
Broken rice	25.6	—	—
Palm oil	—	3	375–412
Glucose	—	3–10	550–600
Lysine	—	0.2	3550
Methionine	—	0.1	2250
Limestone	—	0.7–1.5	36–45
Tricalcium phosphate	—	0.5–1.5	100–210
Dicalcium phosphate	—	0.5–1.5	175–365
Monocalcium phosphate	—	—	385
Salt	—	0.3–0.5	275
Sugar	—	—	385

Table 2.5. Protein and energy content of pig feeds.[a]

Pig type	Crude protein (% of dry feed) Recommended	Crude protein (% of dry feed) Min.	Crude protein (% of dry feed) Max.	Digestible energy (kcal/kg)[b] Min.	Digestible energy (kcal/kg)[b] Max.
Prestarter	18–20	20.5	24	3100	3500
Starter	16–17	18	20	3000	3300
Grower	14–15	16	18	2950	3300
Finisher	12–13	14	18	2850	3050
Gestating	14–16	16.5	18	2900	3200
Lactating	14–18	17	20	2950	3500

[a] These are the minimum and maximum design levels of the rations formulated by commercial pig farmers in Singapore in 1986.

[b] 1 kcal = 4.187 Joules.

Table 2.6. Chemical analyses (%) of pig feed samples taken from 10 commercial farms in 1986 in Ponggol Phase III PFA.

	Prestarter	Starter	Grower	Finisher	Gestation	Lactation
Moisture	9.0–11.4	8.8–11.7	11.1–11.9	10.4–11.8	10.6–11.7	9.9–12.3
Ether extract	3.0–6.0	3.0–5.5	2.0–4.3	2.2–4.4	2.0–5.7	0–7.3
Crude protein	19.1–24.0	17.9–22.6	16.4–19.9	16.5–20.3	14.0–22.3	15.1–21.3
Crude fibre	1.8–7.0	2.6–4.6	4.2–6.7	6.0–8.0	6.0–6.7	4.2–5.7
Ash	4.8–8.4	4.5–6.3	5.1–7.8	7.0–10.6	5.3–8.8	5.5–8.5
Calcium	0.8–2.0	0.9–1.2	0.8–1.2	1.0–1.4	1.0–1.5	1.0–1.2
Phosphorus	0.7–0.9	0.7–0.9	0.6–0.9	0.8–1.2	0.8–1.1	0.6–1.1
1986 price (USD/kg)[a]	0.27–0.46	0.18–0.22	0.17–0.18	0.16–0.19	0.16–0.18	0.17–0.19

[a] As reported by farmers in the 1986 survey.

Feed Consumption

Daily feed consumption varied from about 0.06 kg/piglet to 4 kg/sow. Weaners required about 0.7 kg/day; growers, 1.5 kg/day; finishers and gilts, 2.5 kg/day. Sows in gestation were limited to about 1.8 kg/day. For design purposes, the overall daily consumption for a closed-herd pig farm was assumed to be 1.5 kg/SPP.

Feed Storage and Handling

Bulk Density

The bulk density of the raw ingredients used in the pig feeds varied from 0.25 kg/L for rice bran, to 0.7 kg/L for corn and soybean meal, to 1.5 kg/L for some minerals, which, however, constitute less than 2% of the feed. For design purposes, bulk density was about 0.65 kg/L. For a farm of 6 000 SPP (600 SSP) with an average daily consumption of 1.5 kg feed/SPP, storage of the 9 t of daily feed would occupy a volume of 13.8 m^3. If bulk delivery of feed is used, the volume of feed hoppers for each barn can be estimated from the actual bulk density of the feed plus storage capacity for 3 to 4 days.

Feed Mill and Handling

In Singapore, only corn was available in bulk supply on a regular basis. Soybean meal was occasionally available in bulk; all other feed ingredients arrived in Singapore harbour in bags. It was important, therefore, to mechanize corn handling on the new farms.

Round self-feeders must be placed in the centre of the pen. Straight feeders, with single or double troughs, must be located at the side or end of the pen. Because the feeds in Singapore were high in fibre, they flowed best in a round-type feeder, in which the drum could be turned by the pigs to agitate the feed. Floor feeding requires frequent attention to the amount of feed dispensed and must be adjusted as the pigs grow. The feed should be dropped on the floor several times a day in small quantities. If the pigs do not clean up the feed in 20 min, they will get it dirty and the feed will be wasted. Feed-dropping devices should be controlled by a clock so that the pigs are fed on a regular schedule. Weighing-type dispensers are more accurate and more costly than the volumetric devices. Measuring devices should not drop feed into a feeder or trough unless there is a place for all of the pigs to eat at the same time. In large pens, there should be two or more droppers so all of the pigs can feed at the same time.

Disease Management

Disease and health problems are present at all times, even in isolated, well-run pig farms. Routine diseases can be controlled, but not eliminated, with good farm management and pig husbandry practices. Special efforts are needed to control infectious diseases by vaccinations and veterinary treatment. Health and disease problems are, of course, much more prevalent in intensive pig farming areas where farms are separated only by a fence. Infectious diseases can become epidemic in pig farming areas. This happened in Singapore when Auzesky's Disease reached epidemic proportions and affected a large part of the pig population. Farmers in the PFA had to calculate into their financial projections, losses resulting from chronic disease and health damage.

Major Diseases

The major disease control programs instituted by the Government of Singapore required that the farmers, before moving into the PFA in Ponggol, meet specific conditions on major diseases, such as brucellosis and swine fever, parasitic diseases, and general herd health. No animals that tested positive for brucellosis 60 days before entrance were permitted into the PFA. All pigs had to be vaccinated for swine fever 6 months before coming to the PFA. Deworming was required 30 and 15 days before resettlement. Veterinary inspection took place the week before bringing the pigs into the PFA. Table 2.7 lists pig diseases of importance in the Ponggol PFA, years of severe outbreaks, and numbers of animals that veterinary extension personnel serviced in the 500 000-pig PFA.

As many as 90% of the pigs in a single farm became sick during the height of the Auzesky's Disease outbreak in 1978. About 75% of the piglets that were less than 2 weeks old died. After 3 weeks, infection culminated in 50% deaths; this decreased to 5% after 5 months. In infected farms, 70% of the pregnant sows aborted. The disease was brought under control with vaccination and farm management measures along with controlling the movement of pigs and people among farms.

Routine Health Problems

Transmissible diseases can be minimized by good management practices and farm layout, but some diseases are endemic and must be treated.

Table 2.7. Typical diseases and their frequency (1983–1985) in the Ponggol PFA.[a]

Disease	Major outbreaks (years)	Recorded cases	SPP
Transmissible gastric enteritis	1982, 1983	13	2090
Hemophilus pleuropneumonia	1979	38	1656
Respiratory infection	—	22	1537
Auzesky's disease	1977, 1978	24	1099
Enteritis	—	30	571
Polyserositis	—	4	501
Purulent meningoencephalitis	—	3	501
Swine fever	—	2	257
Post-weaning diarrhea	—	10	231
Salmonellosis	—	7	226
Rhinitis	—	3	217
Swine dysentery	—	9	189
Piglet diarrhea	—	11	182
Nonsuppurative menincephalitis	—	1	150
Cryptorchid	—	80	146
Streptococcal infection	—	6	137
Toxoplasmosis	1976	1	7
Eyrispelas	—	1	5
Brucellosis	—	6	17
Enzoonotic pneumonia	—	—	—
Leptospirosis	—	—	—
Japanese bencephality	—	—	—
Parvovirus	—	—	—
Enterovirus	—	—	—
Parasites	—	—	—

[a] These 25 diseases are considered important in intensive pig feedlot areas such as Ponggol. The statistics on cases and number of pigs are for the years 1983 to 1985 and are not to be taken as the total number of animals infected during that 3-year period. The data represent the animals visited by the Government Veterinary Service at the request of the farmer and may reflect in a qualitative way the prevalence of the disease. The list is limited to 25 diseases that the veterinarians considered crucial, although cases may not have been reported to them.

Scours and diarrhea in piglets and weaners are common and frequent. Vigilant disinfection of farrowing pens before pregnant sows are moved in, and of weaner pens between batches, is essential. Piglets and weaners are very sensitive and vulnerable to bacterial infection, drafts, and changes in temperature. Heat lamps, which maintain temperatures at about 35°C, in a corner of the farrowing pen are used to keep piglets warm. Bacterial infection of teats can cause mastitis in sows, which weakens them and affects milk production. Prevention of lameness in piglets, weaners, and, when moving, sows and porkers is critically important. Parasites may also build up, particularly in the breeding stock, and regular deworming is required.

Black and White System

The basis of the "black and white" system is that "clean" areas (white) should be separated from "dirty" areas (black) on the farm. In addition to the black and white zones, there is a buffer zone (grey area). The system helps prevent the introduction of pathogens into the farm and the spread of disease within the pig herd.

Production Zone (White Area)

The white area contains the pig barns and must be strictly isolated by a fence and locked gate.

Supply Zone (Black Area)

The black area contains the buildings and areas that have frequent and unavoidable contact with external sources: feed storage; administrative building (office, canteen, toilets, and change rooms); delivery points; load-out point; carcass-disposal point; waste-collection point for refuse and garbage; and access roads to the above facilities.

Buffer Zone

The buffer zone is the area around the farm that separates it from other farms. This zone can contain auxiliary facilities that are required by the farm: lagoon; water storage pond and wells; open space, lanes, trees, and garden; and family living area. The buffer zone may also be the space between farms used for public roads.

Management of the System

Feed storage should be located on the border between zones. It is important that the delivery point and feed take-off points are separated. Bulk bins are recommended because they reduce the need for delivery personnel to enter the storage area. Using the farm's own bulk truck to get feed at the mill is better than using trucks that have been to several other farms.

Traffic into the black zone should be controlled by a gate. Traffic from the black zone into the white zone also should be controlled by a gate. Only essential vehicles should be permitted in the white zone, and there should be a wheel-disinfection bath at its entrance.

Traffic lanes and roads should be hard-surfaced for easy cleaning and to avoid mud, which can be tracked into the white zone. Visitors should be discouraged, but visitors should not enter the white zone without changing and disinfecting their footwear.

Workers should be restricted to specific zones, and all workers entering the white zone should change their clothes and disinfect their footwear. All workers should be advised to avoid contact with other pigs or pig farms.

Dead animals should be disposed of promptly. There should be an easy means of moving dead animals to a pick-up point in the black zone. A loader-tractor with a large bucket is recommended because it can move through the white zone to pick up dead animals and minimize dragging of the animals. The loader-tractor can move to the pick-up point and discharge its load directly into the collection truck without either the loader or operator coming into direct contact with the collection truck. The loader-tractor should be washed and disinfected before it returns to the white zone.

Rainwater drainage from the black zone should not enter the white zone. Rainwater that enters the water storage pond should come only from the barn roofs and be collected in eavestroughs (not ground-level concrete gutters) and should be conveyed in closed pipes to the pond. Excess roof water and surface runoff from within the white zone should be diverted to the drain.

The load-out point for market pigs should be on the border between the zones. The load-out facility should be arranged so that farm labour can sort and move the pigs to a single point with one-way gates in the alley. Butchers should be discouraged from inspecting and selecting pigs at the farm because they go from farm to farm buying pigs and are pathogen carriers.

The administration/canteen building should be located on the border between the zones, with outside and inside service areas in both the office and canteen. This facility should also include the toilets and change rooms for the workers, with separate facilities for those who must enter the white zone.

A 2 m high, chain-link fence should demarcate the boundary between the black and white zones. Portions of the buffer zone may lie within the white zone fence, whereas other portions of the buffer zone may lie inside the black zone fence. The water pond and lagoon should not be within the black zone fenced area; family living areas should not be within the white zone. The entire farm should have a 2 m high fence along its boundary.

All-In, All-Out System

The aim of the "all-in, all-out" system is to prevent a build-up of facultative pathogens within the animal production facilities. The basic idea is to allow pens or subunits of the barns to be empty (after cleaning and disinfection) for as long as possible, preferably a minimum of 4 days. This is especially important for farrowing and weaning facilities.

When planning farm layout and building design in an all-in, all-out system, the following points must be considered:

- Subunits must be sized to fit the management plan.
- Space must be increased to allow for filling-up time, emptying time, and resting time.
- Space requirements must take into account management, especially minimum and maximum group size and available labour force.
- Equipment should be selected for ease of cleaning.

Plastic-coated and bare-woven wire are preferred over wood or concrete slats. Stalls and pens should not have open-ended pipes, which are hard to clean. Smooth tubes and rods are preferred over deformed reinforcing rods. Galvanized metals are more durable under the forces of high-pressure cleaning equipment than is painted equipment.

Water

Water Needs

Each day, water supplies must provide 7–10 L/SPP for drinking, 1 L/SPP for disinfection of farrowing and weaner pens, and 12–50 L/SPP for hosing the floors, cleaning the pigs, and removing wastes from the pens and barns. The daily water usage was 20 L/SPP in Singapore.

Water Quality

The quality of drinking water must be as near to human potable water as possible. Table 2.8 shows potable water quality levels recommended for pigs. Groundwater and pond water commonly used in the farms in the tropics rarely meet these standards.

Water for hosing was normally supplied from water ponds fed by rainfall runoff. If a slotted floor over a channel is used, low-quality lagoon water can be recycled to remove the wastes from the channel.

Rainfall Catchment

The rainfall catchment area in a pig farm in Singapore consisted of the roof of the barns and other buildings (about 2 m^2/SPP with a runoff coefficient of 1.0); the pond itself (a surface area of 0.5 m^2/SPP with a runoff coefficient of 1.0); and the spaces between buildings (1 m^2/SPP with a runoff coefficient of 0.6). A total of 3.5 m^2/SPP with an overall runoff coefficient of 0.89 amounted to 3.1 m^3/SPP per metre of rainfall.

Annual rainfall in the tropics is 2–3 m/year. In Singapore it was 2.4 m/year, with an average of 0.16 m in July and 0.28 m in December. With a collection efficiency of 3.1 m^3/SPP per metre of rainfall (as calculated above), the volume of water that could be collected in the Ponggol

Table 2.8. Quality parameters of potable water for livestock.[a]

Parameter	Maximum	Minimum	Acceptable	Tolerable
Fertilizer chemicals (mg/L)				
Nitrate nitrogen (TNN)	44	0–10	10–22	—
Nitrates (TNA)	200	0–45	45–100	—
Total dissolved solids (TDS)	5000	500–1000	1000–3000	—
Magnesium	30–90	0–30	30–60	—
Calcium	200	0–50	50–80	80–200
Sodium	0–30	150	30–50	50–150
Chloride	300	0–70	70–150	150–300
Sulfate	300	0–75	75–150	150–300
Sulfate sulfur (SOS)	100	0–25	25–50	50–100
Chlorinated hydrocarbons (ppb)				
Endrin	0.2	—	—	—
Lindane	4.0	—	—	—
Methoxychlor	100	—	—	—
Toxaphene	5.0	—	—	—
Herbicides (ppb)				
2,4-D	100	—	—	—
2,4,5-TP (silvex)	10	—	—	—
Toxic chemicals (mg/L)				
Arsenic	0.2	—	—	0.05
Boron	30	—	—	1.0
Cadmium	0.05	—	—	0.01
Chromium	1.0	—	—	0.05
Copper	0.5	—	—	—
Fluoride	2.0	—	—	0.6
Lead	0.1	—	—	0.05
Zinc	25	—	—	—
Iron	—	—	0.3	0.5
Manganese	—	—	0.05	—
Mercury	0.01	—	—	0.002
Biological content				
Bacteria	No pathogens, absence of coliforms and toxic algae			
pH	10	6.0	6.5–8.0	8–10

[a] Water used for hosing pen floors or for flushing wastes can be of lower quality. Generally, pigs drink 1 L of water per kilogram of feed eaten. Saline water (TDS > 1500 mg/L), although accepted by pigs, may cause diarrhea in young animals. High sulfate content may also cause diarrhea. Excessive nitrates can be fatal to piglets.

PFA averaged 0.50 m^3/SPP in July and 0.87 m^3/SPP in December. These volumes on a daily basis are 16 L/SPP in July and 28 L/SPP in December.

Water Storage

Although the annual average water catchment was equal to the daily requirement of 20 L/SSP, daily rainfall could be as low as 0.008 m which amounted to less than 1 L/SPP and as high as 85 L/SPP during high-rainfall periods. Therefore, it was necessary to collect and store the oversupply during the rainy period to provide for the drought periods, which occurred mostly between January and May.

The water storage suggested for Singapore farms, where land was limited to 5 m^2/SPP, was the volume required for 100 days. At 20 L/SPP per day, a volume of 2 m^3/SPP was needed. With 1.6 m of annual evaporation from the 0.5 m^2/SPP pond (or 0.22 m^3/SPP for 100 days) and 15% miscellaneous losses (0.3 m^3/SPP), the total losses would amount to 0.52 m^3/SPP. Thus, the total 100-day storage would need to be 2.5 m^3/SPP. For a 6 000-SPP farm, a pond with 15 000 m^3 capacity would be required.

Rainfall Collection

The rainfall-collection system consists of eavestroughs, closed pipes, and channels to drain the collected rainfall to the pond. For the design of the eavestroughs and channels, the peak runoff is calculated using the rational formula:

$$Q = (1/360)CIA$$

where Q is the peak runoff (m^3/s); C is the runoff coefficient, which is assumed to be 1.0 for roofs and 0.6 for soft ground; I is the rainfall intensity (mm/h) (this must be obtained from rainfall frequency duration curves — for Singapore, and a 3-year recurrence interval, $I = 200$ mm/h; for a 10-year recurrence interval, $I = 250$ mm/h); and A is the draining area (ha).

The design of the eavestroughs and drains was based on the standard Manning formula found in all hydraulic textbooks. Concrete drains of standard shape were recommended to maintain water quality and minimize losses.

Behaviour Traits

Pigs are curious animals. They readily learn to open the lid of a self-feeder or push a valve for water. Even newborn pigs, whose suckling instinct is highly developed, can be taught to drink from a bowl when weaned from their mother. Individual pigs within litters establish teat position within the first week when suckling the sow.

Pigs like to nibble at food. Therefore, if food is offered freely from a self-feeder, the total daily intake will be spread over many small meals throughout the day. The daily food intake of young pigs is reduced if one or two meals are provided per day to satisfy appetite. For older pigs approaching market weight, daily food intake with one or two meals a day is equal to that achieved with continuous feeding.

Pigs tend to be good housekeepers when given the chance. If the sleeping area is restricted, they usually use a corner of the pen away from the sleeping area to defecate and urinate. Because pigs cannot dissipate body heat by sweating, high ambient temperatures encourage wallowing to keep cool.

During gestation, sows tend to become more docile, especially as they approach farrowing. Labour produces restlessness, repeated rising and lying, and straining. When farrowing begins, the sow usually remains lying until the last pig is born. Milk letdown is continuous during farrowing and first-born pigs find their way to a teat before their littermates are born. Occasionally, sows are hostile to their piglets during farrowing and may bite them, causing serious injury or even death.

Social dominance is evident very early in the life of the pig, e.g., establishment of teat position. This same social dominance is shown when strange pigs are penned together after weaning. There is fighting, which ends when a social hierarchy is established. The same pattern exists when sows are kept in a group in a pen with limited feeding space.

Basics of Pig Management

In pig production, housing and management must be considered together because one complements the other. Pig production methods need to be adapted to the requirements of intensive systems that have mechanization and low-labour confinement facilities. The management principles on which emphasis must be placed include the following:

- selection and use of good breeding stock,
- nutrition and feeding of pigs to provide for optimum production during all stages of their lives,
- provision of favourable housing (accommodation and environment),
- general management of animals at breeding, gestation, farrowing, lactation, and growth to marketable weight,
- maintenance of proper and effective disease-control programs,
- keeping of sufficient records to check on the cost of production and to assist in organization and management, and
- gearing, channelling, and timing pig production to the available markets.

Questions and Answers

Question 1. What breeds of pig were used in Singapore?

Answer 1. Production pigs were introduced to the Malay Peninsula by Chinese immigrants in the 17th century. Pig rearing became a business in the 1870s during the boom years of tin mining, which attracted a large influx of Chinese workers. Pigs were reared around tin-mine settlements and supported mainly with food leftovers. The first breeding farms were established in the 1920s, and breeding programs centred around mating the Chinese sows with European stock such as Poland China, Middle White, and Large Black boars. Later, Large White and Yorkshire pigs from England and Landrace from Denmark were brought in; by the 1940s, crossbreeding became acceptable and widely practiced.

In the 1970s, farmers began to import purebred pigs from Europe and North America. In 1982, a commercial farm in Phase III PFA arranged to have a cargo plane loaded with 1 500 breeding stock selected from breeding farms in the United States and flown directly from Chicago to Singapore. It was claimed to be the longest flight of this type ever attempted. A similar trip was tried just as successfully in 1987 when a new commercial farm for 500 000 SPP was started on an Indonesian island next to Singapore. Although there were some commercial breeding farms both in Singapore and neighbouring Malaysia, most of the breeding stock was imported from Europe, North America (Canada and the United States), and from Australia. Duroc boars predominated in the 1980s; Yorkshire and Landrace were the main sow lines.

Question 2. What makes pigs attractive for commercial production?

Answer 2. Pigs and pig meat are an excellent source of protein, vitamins, minerals, and energy. Pigs have a short reproductive cycle and are very prolific. Because they are omnivorous, pigs use a wide range of feedstuffs, some of which are unsuitable for human consumption. However, in Singapore, as in all other parts of the world, commercial farmers fed pigs grain-based feeds (see Table 2.4). Pigs grow quickly if they are given the right feed ration and proper husbandry.

Question 3. What are the major cost components in commercial pig production?

Answer 3. The cost of pig production was estimated by the farmers to be 1.12 USD/kg animal live weight (ALW). This was an ex-farm price paid by butchers. Cost components can be grouped as follows:

- annualized initial costs (AIC) for housing, feed milling, and waste lagooning facilities over an amortization period of 15 years;
- annual waste disposal costs (AWC);
- annual labour and management costs (ALC);
- annual cost of replacing breeding boars and losses as a result of mortality (ABC);

- annual costs for utilities, repairs, maintenance, and operation of farm equipment (AUC); and
- annual feed costs (AFC), which include medicine and drug costs as well as veterinary and nutritional advisory services.

These groups account for the following proportions of the total cost of commercial pig production: AFC, 75.4%; ALC, 13.0%; AIC, 5.3%; AUC, 4.2%; ABC, 1.7%; AWC, 0.4%. AWC was estimated at less than 1% because it was based on desludging and not on treatment. Treatment costs are presented in subsequent chapters.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Productivity parameters and porker marketing trends and prospects at the local, regional, and national levels.
2. Production cycle, husbandry practices, breeding programs, and life cycle of pigs in commercial enterprises.
3. Feeds and feeding: ingredients, formulations, rations, materials handling, nutrition, and toxicity.
4. Water: standards for drinking by livestock, supply, demand, storage, and delivery.

Chapter 3

Pig House Ventilation in the Tropics

This chapter briefly describes the factors involved in pig house ventilation and the analyses carried out. It then reviews the recommendations of expert consultants whose opinions on important ventilation issues are discussed in the question and answer section. The chapter should be most useful to design engineers and scientists who are planning and managing pig farming areas.

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General Background on Ventilation

Pigs must have evolved in arid regions. Unlike humans, who are also homeothermic (i.e., body temperature is kept at a constant level in all ambient conditions), the sweat glands of pigs are plugged with keratin. Consequently, they cannot dissipate heat by sweating the way we do. Instead, pigs, whose body temperature is 39°C (close to ours, 37°C), increase their respiration rate when they are excessively hot. Metabolic activities decrease as the temperature and relative humidity increase; whereas the respiratory rate increases as pigs try to lose heat through breathing. This stressful situation reduces the growth rate of pigs. In commercial production in warm climates, therefore, proper ventilation is important to prevent the temperature from rising beyond the comfort level of the pigs.

The pig houses built in Singapore before 1979 provided protection from sun and rain. They were pole-framed buildings with a roof but no walls. The principal problem with these barns was that the ventilation was insufficient to remove the heat generated by the animals as well as the heat produced by radiation from the hot roofs. Close spacing of the buildings and low natural wind velocities made ventilation a big problem.

Heat Stress

The efficiency of weight gain of porkers is greatly reduced as the temperature of the pig's environment approaches 32°C. The performance of sows during farrowing is also affected by heat stress. Conception rates may be reduced to 30% from the normal 80%. Boars subjected to a 1 Celsius degree rise in body temperature will have reduced semen quality for 4 to 8 weeks, and females bred to these boars will have lower conception rates and smaller litters. Gilts and sows are also affected by temperatures above 29°C. Heat stress will delay or prevent occurrence of "heat" (estrus), reduce ovulation rates, and increase early embryonic deaths.

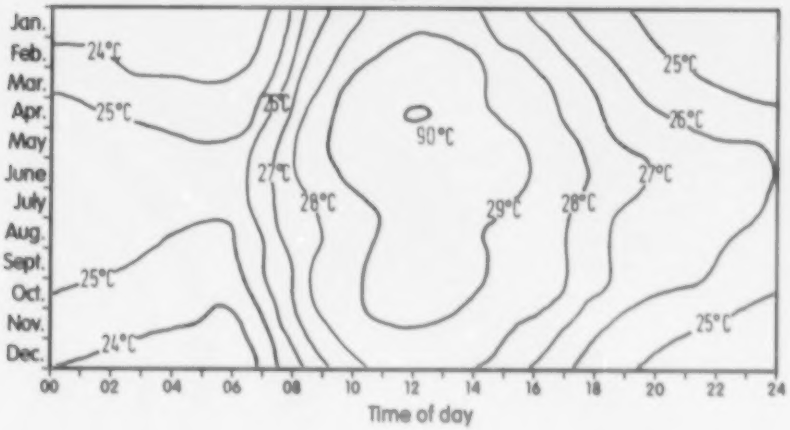
Pigs maintain an average body temperature of 39.2°C but their temperature can range from 38.7 to 39.4°C. An increase in body temperature of only a few degrees can be fatal. Internal body temperature is controlled by a dynamic equilibrium between heat produced internally and heat lost to the environment. The animal produces heat when it transforms the chemical energy of feed into work. Of the gross feed-energy consumed by the pig, 25–40% is converted into heat and lost to the environment. The rate of internal heat production varies with size, body weight, breed, health, stage of growth, nature and rate of feed intake, level of production, gestation, age, degree of activity, and environmental conditions.

Baby pigs do not have a well-developed homeothermic system. Therefore, they must be protected against chilling during the first few weeks of life.

In commercial pig production the critical temperature is 28°C. If that temperature is exceeded continuously for 12 h in the pig house environment, it is absolutely essential to provide artificial cooling. Figure 3.1 shows that the mean temperature in Singapore was at or above 28°C for at least 6 h per average day (1030 to 1630). Mechanical cooling (air conditioning) was prohibitively expensive and evaporative cooling was not feasible because of the high relative humidity (Fig. 3.1) and the fact that the barns were open on the sides. Therefore, the work in this area concentrated on roof design, building width, and spacing to maximize natural ventilation.

In Singapore, the main consideration in animal comfort was to remove heat from the animals and their surroundings. The heat generated by the

Temperature



Relative humidity

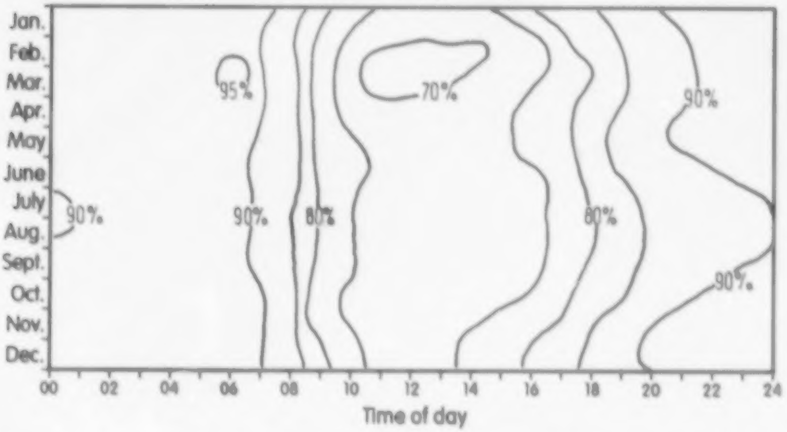


Fig. 3.1. Mean hourly temperature and relative humidity for each month of the year in Singapore. The mean values are based on a 45-year record.

animals and radiated from the roof would make the temperature in the confinement buildings high unless good ventilation carried the heat away.

Heat Loss Avenues

There are four ways for animals to lose heat: conduction, convection, radiation, and evaporation. The total heat exchanged hourly between an animal and its surroundings consists of both sensible heat and latent heat. Sensible heat transfer is governed by the mechanisms of heat transmission (conduction, convection, and radiation). All animals dissipate significant amounts of latent heat by vaporization, or moisture evaporation, from the respiratory tract and body surface. When the ambient temperature is greater than the surface temperature of the animal, sensible heat is gained by the animal instead of lost.

Conduction

Conduction is heat transfer between bodies in direct contact, because of a temperature difference, and without gross movement of the material. Heat transfer from the body core to the skin surface occurs by conduction through body tissue and also by convection associated with blood flow. Many animals adjust to conductive heat loss simply by changing contact area (huddling with a warm or cold animal, or standing up from a cold or hot floor).

Convection

Convective heat exchange occurs during air movement around the animal and is due to temperature or pressure differentials or mechanical causes. Fans, pumps, or blowers produce fluid motion and heat transfer known as forced convection. The combined effect of high air velocity and cool ambient temperature results in high heat loss from livestock by convection to the air. When the ambient air temperature equals the body's surface temperature, convective heat transfer from the skin is zero.

Radiation

Heat is radiated from a hot body to a cooler one. Therefore, a hog loses some heat by radiation to cooler floor and wall surfaces nearby. However, the animal also gains considerable heat by radiation from the roof and other exterior surfaces that are heated by the sun to a temperature above the pig's body temperature. Radiation heat gained from the roof and through the open sides of the shelter adds to the total heat the pig must dissipate by convection and by evaporation.

Evaporation

Evaporative heat loss is principally due to moisture added to the air through the pig's respiration. Any evaporation of moisture applied to the hog from outside sources also contributes to cooling. Moisture that evaporates from floors, walls, or other surfaces also tends to cool the air around the hog. Moisture loss through the skin is minimal in most domestic animals (cattle, swine, sheep, poultry); evaporative loss is largely from their respiratory tracts. Expired air, heated nearly to body temperature and saturated with water vapour, is exhaled as liquid water vapourized in the upper respiratory tract. Little water evaporation or air warming takes place in the lungs.

Nonsweating species adjust to high temperature stress by greatly increasing their respiration (panting). Animal skin surfaces can be wet to maximize cooling by external evaporation.

Climatic Conditions in Singapore

Singapore is only a few degrees north of the equator and has a consistent daytime temperature of 25–29°C. The average relative humidity, over the past 45 years, shows some variation during the day, but is quite consistent throughout the year (Fig. 3.1). The lowest relative humidity is slightly above 70% in the middle of the day when the temperature is at its highest. This is the point that was analyzed in detail because it is critical to pig production.

Singapore does have some seasonal variation in mean sunshine hours and hourly radiation (Fig. 3.2). November is the cloudiest month; March, the clearest. The maximum, mean, hourly solar radiation of 61 mW/cm^2 varied from a maximum of 70 to a minimum of 55 mW/cm^2. Cloud cover, rainfall, and radiation affected temperature and humidity levels; however, for the purpose of analyzing animal stress, the midday, long-term averages of temperature and humidity were used.

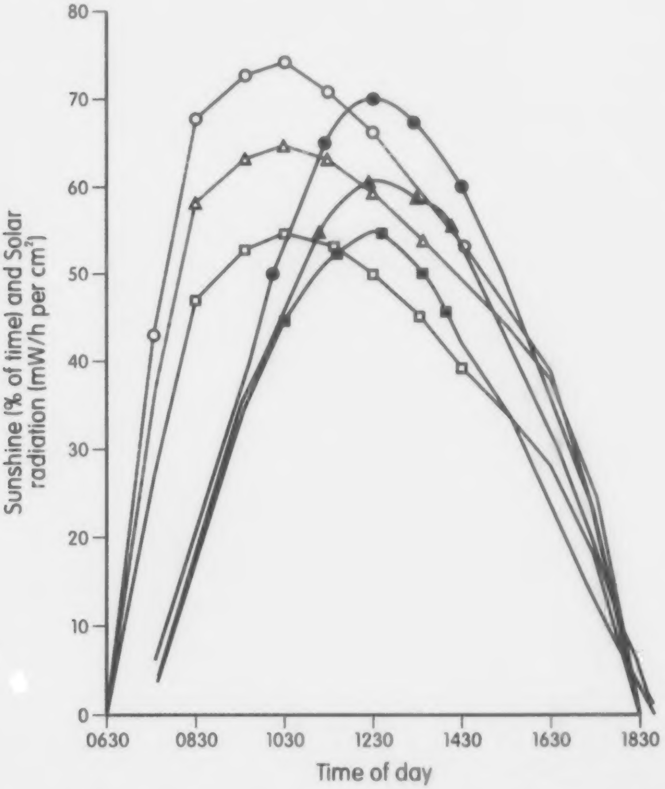


Fig. 3.2. Solar radiation (solid lines) and sunshine hours (dashed lines) in Singapore (○, ●, March; △, ▲, mean; □, ■, November).

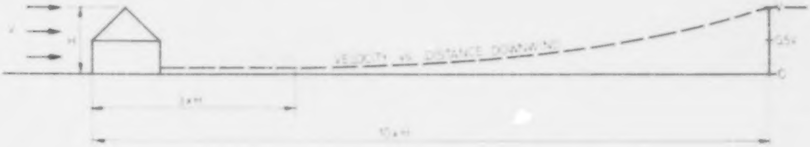


Fig. 3.3. Wind velocity (*V*) pattern between barns. The effect of one building on the next was estimated by using the empirical formulas for wind breaks. The effect of the shape of the barn was examined using empirical formulations for gravity up-flow ventilation in chimneys.

Theoretical Considerations

For ideal natural cross ventilation, each building should be built with open side walls on an isolated hill. The building would then depend upon the wind to provide sufficient ventilation.

Figure 3.3 illustrates the windbreak effect of one building on the next. This analysis estimated that the optimum spacing for wind ventilation would be at least 60 m. Spacings of 20 m or less resulted in negligible wind ventilation.

If building spacing cannot be at least 20 m, then it should be sufficient only to allow unrestricted entry of air under natural convection or gravity up-flow ventilation (Fig. 3.4). The basic principle in gravity ventilation is that incoming air is heated by the livestock and radiant energy from the roof creating a differential in air density. This air density differential causes the air to rise, forcing air out the top of the building, carrying with it the heat dissipated by the pigs and the building.

Theoretical analyses using equations for air velocities induced by temperature changes showed that the most effective way to reduce the building temperature was to reduce the heat load within the building. Furthermore, the most effective way to reduce the heat load was to reduce the solar effects within the building.

Solar effects can be reduced by changing the roof colour, so that the outer surface of the roof has a higher reflectance and the inner surface has a higher absorption of solar radiation. In general, this would mean a roofing material with a white top and black bottom. Solar effects can also be reduced by insulating the roof and thus lowering the temperature of the radiant surface.

Stocking Density

A reduction in animal density will also reduce the heat load and building temperature. However, the heat produced by the animals accounts for a very small percentage of the total. If, for example, all the pigs were removed

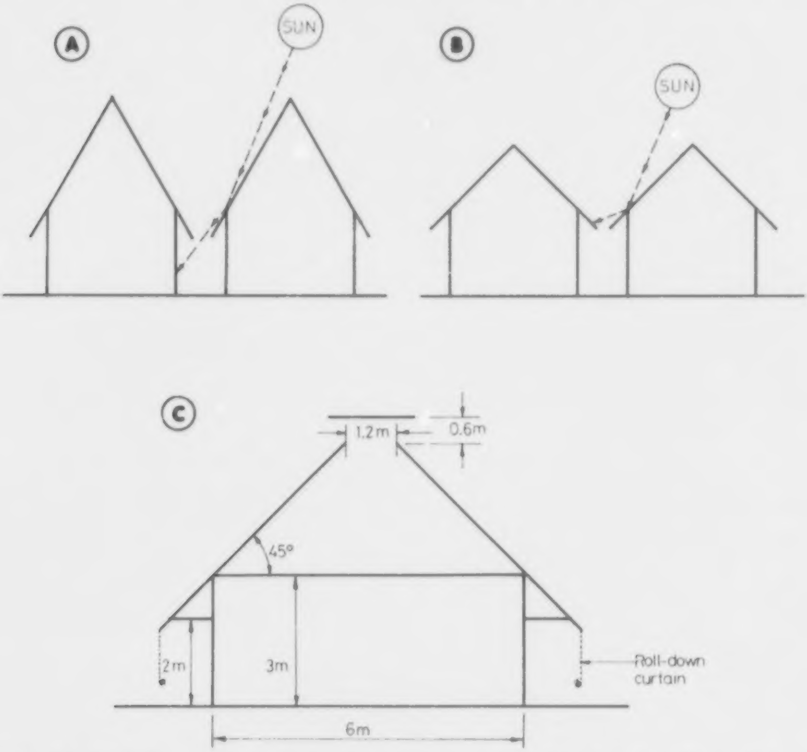


Fig. 3.4. Models used in designing barn features. To determine the effects of the various parameters in gravity ventilation, the building was assumed to be a firebox chimney with a constricted exhaust at the ridge and an intake at the side wall near the floor: (A) steep roof; (B) 45° roof; (C) rough dimensions of design structure.

from the building, the temperature would be reduced by only 0.2 Celsius degrees.

Ridge Opening

For the restriction on the entering air to be considered negligible, the distance between the eaves of two adjacent building must be at least twice the width of the roof ridge opening. For the air to be forced to enter at floor level, the building eave or wall must extend down to the ground. However, to avoid creating another restriction, the opening distance must be more than one half the ridge opening width. This would assume that the ridge was open and unrestricted. This is impractical because an open roof ridge would allow rain and direct solar radiation to enter the building.

Therefore, some protection must be developed for the opening while maintaining the least restriction. Although the actual air flow and temperature differential inside the building may be significantly different from those calculated under these assumptions, the basic relative value and conclusions would be as projected. The cover of the roof ridge should be raised so that the opening area on each side is at least half the width of the ridge.

Barn Width

Increasing the width of the barn would increase the heat load. However, this could be compensated for by increasing the height and ridge opening. The major consideration then becomes one of air movement or velocity within the building. As air enters at the floor level, it has a certain velocity. As it moves into the building, it begins to spread and rise and loses most of this velocity. If the building is too wide, fresh, cool, incoming air does not reach the middle of the building before it is heated and rises. This leaves a dead air space in the centre of the building where air becomes stagnant and remains hot.

Theoretical Designs

Roof Slope

The roof slope was set at 45° (i.e., 1:1 grade). The roof was steep enough to maximize the building height without excessively increasing the structural costs. A very steep roof would reflect solar radiation into the wall opening of the adjacent barn (see Fig. 3.4). This affects eave height as well as roof slope. For this reason, the eave height should be decreased to 1 m by rolling down a nonreflective curtain to block solar radiation.

The curtain can be canvas, burlap, or bamboo strips. The curtain should be rolled down to 1 m off the ground on very calm days and rolled back up on windy days to take advantage of any air movement. When fully lowered, the curtain can also protect small pigs in farrowing and nursery pens from drafts.

Roof Materials

The best roofing material is corrugated aluminum with a black undersurface. Such material is created by painting the underside of the aluminum sheet black or, better still, by lining the underside of the purlin with black polyethylene plastic or another dark material. This creates an insulating dead air space. Aluminum roofing with a black bottom surface is 15% more effective at keeping radiant energy from reaching the shaded floor surface than cement asbestos board. Galvanized steel with the bottom painted black is 1% less efficient than aluminum.

End Walls

The end walls should also be covered with aluminum roofing material from within 1 m from the ridge to 2 m from the floor. The building should be oriented along an east–west axis to prevent morning and evening solar heat entering the long sides. The curtain can also be extended completely around the building, except to allow access. This curtain is adjustable and management is required to obtain optimum benefit from it.

Barn Width

Clearance inside the building was set at 3 m. This was a compromise between height and construction material costs. The area outside the support posts but under the eave overhang should have a clearance of 2 m so that it can be used as a walkway. The overall width of the building was 8 m. This was based on two factors: the size and spacing of equipment and materials inside the building; and the need for a narrow enough width to prevent air stagnation near the centre. Although this dimension may be varied somewhat to fit different uses, a building 25% or more wider will likely not provide sufficient ventilation near the centre.

Ridge Shape

The barn centre ridge opening should be covered with a flat jack roof. The flat ridge roof offered the most protection from rain and sun while offering the least restriction to air flow. The opening between the jack roof and where the roof steel ends must be at least half of the width of the ridge opening. The ridge opening was set at 1.2 m as a practical maximum for efficient construction. Where feasible, however, a wider ridge opening should be encouraged. A multiple-tier roof was rejected because the overall net effect would not justify the additional construction costs.

Trees

Trees planted between the buildings should have long trunks and high, bushy foliage. It was estimated that the cooling and shade benefits from these trees would more than pay for their cost. Bushes would be counterproductive.

Natural Ventilation

Natural wind forces provide the primary means for air movement through open structures. Building construction, roof shape, pen partitions, and equipment all should be designed and laid out to minimize the obstruction of air flow. Air, like water, flows in the path of least resistance. If the path is obstructed, it will not flow at all.

Porker Pens

All barriers to natural air movement should be removed.

- Side walls should be open to a height of at least 2 m.
- Pen partitions should be made of wire or light steels rods.
- Buildings should be narrow to allow space for only two rows of pens.
- The space between barns should be 3–4 m to minimize reflection of

sunlight into the next barn from roofs (larger interbarn spacings were not possible in Singapore).

- Bushes surrounding buildings should be removed and tree trunks trimmed to a height of at least 3 m to prevent obstruction of air movement.

Farrowing Barns

Farrowing buildings should be made as comfortable as possible for the sows, but provide protection for the small piglets. This means opening the buildings for maximum natural air flow for the benefit of the sows. The large, lactating sows are more subject to heat stress than any of the other pigs. The conflict is that the sows need a cooler environment for maximum comfort and the piglets need to be warm. If the entire farrowing house is closed to provide a warm environment for the piglets, then the sows suffer. It is more practical to open the farrowing house for the benefit of the sows and protect the piglets with a windbreak box (burlap bag around a reinforcing rod frame) and provide supplemental heat with a heat lamp.

Ridge Design

The ridge design assists natural air flow. Unobstructed natural horizontal air flow is of primary importance. Ridge openings are necessary and should be designed properly, but are secondary to wind forces. The opening at the top of the main roof should be at least 15% of the roof width. The vertical clearance under each side of the ridge cap should equal 50% of the main opening.

Mechanical Ventilation

Fans

Mechanical fans are best used only to assist natural air flow. Fans should be considered only as a last resort in emergency situations or in poorly constructed buildings that would be too expensive to modify. The capital investment in fans is substantial and the cost of operation is high. Particularly for new pig houses, it is much less costly to build narrow, open buildings with ample space between them than to rely on fans. A survey of 10 commercial farms in Singapore showed that all but 2 used ceiling fans, which were turned on between 1000 and 1640. The temperature in these farms averaged above 28°C from 1000 until 1600; therefore, mechanical ventilation was deemed necessary by the farmers.

Evaporative Cooling

Because of the high relative humidity of the air in tropical climates, the actual reduction in air temperature with evaporative cooling is small and, thus, this method is not advised. The water content of the air increases as it passes the cooler. However, unless this air can be distributed over the bodies of the pigs, even the little benefit derived cannot be realized. In open buildings, uniform distribution of air is not practical. No farmer in Singapore attempted this type of cooling.

Reduction of Radiation Heat Loads

The roofs of pig houses must be designed to be effective shields against solar radiation, but must not obstruct free, natural ventilation. The effectiveness of the roof depends on orientation of the barn to provide shade; roof shape, height, and spacing; and texture, colour, and insulation properties of roofing material. The use of the ground space between the barns can also affect the radiation heat load on the pigs.

Barn Orientation

The pig barns need to be positioned so that the long axis of the roof is in an east–west direction to minimize direct solar radiation. The end pens in the barn can be protected with overhangs or vertical end walls to keep out the early morning and late evening sun. Many combinations of lowered eaves and angled louvers can be used to reduce further penetration of direct solar radiation into the pen area of the barn.

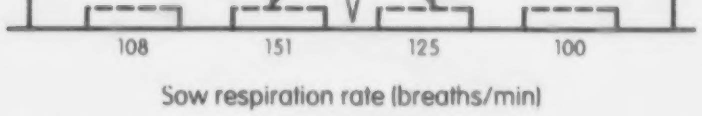


Fig. 3.5. Respiration rates of sows in a wide barn. Rates were measured by counting the number of breaths taken by the animals over a period of time. The sows in the centre rows respired 125–150 times per minute. They were living under roof temperatures of 43–46°C. The respiration rates of the sows in the outer rows, which were insulated as shown, were 100–108 breaths/min. The normal rate is 40–70 breaths/min.

Roof Material

The effectiveness of roofing materials depends on their irreflecting and reradiating capabilities. Both of these characteristics should be maximized for maximum effectiveness. However, surface characteristics change rapidly with age, particularly in tropical climates. Cement asbestos roofing turns black and aluminum surfaces darken and tarnish considerably with time. These were the two most common roofing materials used in Singapore for pig and poultry barns.

When the roof temperature is greater than the surface temperature of the pigs, the pigs gain radiant heat that must be dissipated by increased respiration. Figure 3.5 shows the respiration rates for sows in a farrowing house where the ambient temperature exceeded the body temperature. The respiration rates for the sows in the centre pens of the wide barn were 25–50% higher than those in the outer rows. The sows in the outer row of pens were under less stress, partly because of the fabric shield suspended below the roof, but their respiration rates were still 2–3 times higher than the normal respiration rate of 40–70 breaths/min in a nonstressful environment.

Questions and Answers

Sources of Heat

Question 1. What is the major cause of heat build-up within open pig or poultry barns in the tropics?

Answer 1. If the pig or poultry buildings are open in all ways possible (e.g., no side walls, no air-flow obstructions, good sized continuous ridge ventilators, open pen walls, trees with trunks at least 3 m high, and spacing between buildings of 3–4 m), then the major cause of heat build-up would be radiation. The lower roof surface temperatures of 40–50°C measured in a number of traditional pig barns is a direct indication of the radiation load being added to the animals housed below.

Question 2. How can the heat load from each of the various sources be isolated and quantified?

Answer 2. It is very difficult to quantify, with any degree of accuracy, the separate sources of heat in pig and poultry barns. Sophisticated research laboratories and involved mathematical calculations would be needed. The overall effect of the various heat sources can be measured quite simply and effectively under field conditions with a black globe thermometer, a wet and dry bulb thermometer, and an air velocity anemometer. From these measurements, the mean radiant temperature and radiant heat load can be determined.

Question 3. If barns are close together, say 4 m between eaves, the reflected and reradiation effects contribute different proportions to the overall heat load compared with the isolated case of providing shade in a desert setting. If the space between barns was planted with grass, would bare aluminum roofing be better than black-bottom aluminum?

Answer 3. If all reflective shortwave radiation was eliminated between buildings, which is the case with grass, the bare aluminum surface would be a better shade material. The aluminum surfaces do not stay shiny very long, however, even under the roof in livestock buildings. Therefore, the question of one or the other, bare or black-bottom, is not practical.

In any case, the effect of the undersurface colour of the roof in Singapore conditions is not great compared with other characteristics such as top-side reradiation and, possibly, insulation below the roof. The aluminum roof gets hotter than the darker cement asbestos although it is a better reflector. The problem is that the aluminum absorbs considerable solar radiation and then has trouble reradiating it either upward or downward, so it gets hotter. This higher temperature tends to nullify any benefit that the lower-radiation undersurface may have.

Question 4. Can the amount of heat reflected from the roof of an adjacent barn be computed?

Answer 4. Some theoretical analyses can be made for comparisons between such characteristics as roof slopes, building spacing, etc. Realistic quantitative values are difficult to obtain because of the variance in reflectivity of different materials. The black globe thermometer gives the most representative measure of the effect upon the animal. Black globe measurements, with and without the reflecting surface, would provide the basis for any differential effect. In this case, it must be possible to shield out the reflection for one set of readings.

Roof Material

Question 5. Does the difference in roof effectiveness justify the extra expense of using painted steel or aluminum over corrugated asbestos cement?

Answer 5. None of the tests carried out indicated that the metal roofs were better than cement asbestos or that painted metal roofs were better than painted cement asbestos. Preliminary surface temperature measurements indicated that unpainted cement asbestos was 6–11 Celsius degrees hotter than painted cement asbestos (both aged) and that white-painted aluminum was 1–4 Celsius degrees hotter than painted cement asbestos (new paint). The lower downward-reradiating characteristics of aluminum should compensate for the higher surface temperatures. Long-term tests of comparative barns with various roofing materials would be necessary to determine if there were any production improvements or savings.

Question 6. In Singapore, there is rapid deterioration of corrugated tin and aluminum roofing sheets. Is this because of salt air from the sea, high humidity, or poor quality of materials?

Answer 6. It is doubtful that the deterioration of corrugated galvanized steel and aluminum roofing sheets is more rapid in Singapore than in other hot tropical countries. The high temperature and humidity combine to accelerate the deterioration process. Moisture is necessary for any deterioration process; higher temperature accelerates both biological and physical processes.

Question 7. How is the benefit calculated of using insulation under the roof sheet to reduce heat?

Answer 7. Reduction of surface temperature is a direct indication of the reduction of the radiation load below the pig barn roof. The closer the undersurface temperature is to the air temperature the better, regardless of how it is done. The other factor is cost on a long-term basis. If the different materials and surface changes provide comparable reductions in surface temperature and surface emissivity, then cost becomes the main factor.

Question 8. Why do corrugated asbestos cement roofing sheets turn black after a year or so?

Answer 8. Cement asbestos sheets turn black because of the high temperature and humidity, the same factors that cause discolouration of metal roofing materials. Whether the deterioration process is biological, physical, chemical, or a combination thereof, is not known.

Roof Shape and Natural Ventilation

Question 9. When barns are spaced at 4 m eave to eave, which roof shape gives the best environment and why?

Answer 9. The low- to medium-pitched gable roof (about 4 vertical to 12 horizontal, 18° slope) is most practical and effective with the 4 m or narrower spacing, provided it has a ridge opening of at least 1 m effective width. There is no evidence that the steeper 6 to 12 (27° slope) roofs justify the extra construction cost through better thermal convection and air movement. Natural wind convection forces are most dominant in ventilation-air exchange and everything possible should be done to provide freedom for such movement. The 1 or 2 additional difference in temperature that may be gained from the stack action of the steeper roofs and taller buildings will not move enough extra air to justify the additional costs.

Question 10. Barn width is a factor in ventilation, but is there significant deterioration in going from barns 8 m wide at 4-m spacing to barns 12 m wide at 6-m spacings?

Answer 10. Pig barns should be not wider than two rows of stalls for farrowing, or 8 m, in any case. The 8-m width with 4 m between barns provides much better ventilation than 12-m houses with 6-m spacing eave to eave.

Question 11. Can barn width be related to cost of construction and production efficiency? In other words, are narrow barns cheaper and better in a tropical climate?

Answer 11. The improved performance of pigs housed in narrow buildings will far outweigh the small extra construction cost.

Question 12. Can temperatures in the roofs of different shapes of barns be predicted?

Answer 12. The change in temperature in a pig barn as a result of different roof slopes or shapes is only a matter of 1 or 2°, assuming that all gable roofs have an effective ridge ventilator and none is too wide. The major benefit is derived from lining or painting the roof, regardless of its shape or slope, and from providing an opening for good air flow. To a limited extent, the temperature of barns with different roof shapes can be analytically predicted, but errors in assumed roof surface conditions and climatic factors can override the small difference that roof shape may make.

Question 13. What instrumentation is needed to get relevant field data quickly?

Answer 13. The following instruments are needed to make quick environmental temperature measurements: wet and dry bulb thermometer; black globe thermometer; surface temperature probes, both contact and infrared; and hot wire anemometer for air movement. For long-term tests, thermocouples and automatic recorders would be desirable.

Question 14. Will the more efficient roof styles pay for themselves in better animal performance over 15 years?

Answer 14. No. There is no real difference in productivity between roof shapes for similar narrow buildings with good ridge ventilator openings.

Question 15. In land-short Singapore, people always talk about multistoried pig or poultry barns. How practical or feasible are they?

Answer 15. Multistoried pig barns are not feasible because of, among other things, their ventilation requirements, waste handling difficulties, animal movement, and structural costs.

Question 16. What would be the open-space requirement between multistoried units?

Answer 16. There is no practical spacing between multistoried pig barns that would allow adequate natural ventilation to the lower stories of the units. The spacing would have to be at least double that for a single-storied structure, and the lower stories would still need mechanical ventilation. The lower stories, although shielded from most solar radiation by the upper stories, could not have any centre ridge ventilation.

If two-storied units are considered, the lower stories should be closed and mechanically ventilated. These buildings would also require mechanical cooling. In hot weather, livestock buildings must have a minimum of one natural air change per minute. This is a large amount of air to move mechanically.

Question 17. Can the open ridge be made too wide?

Answer 17. No. The ridge cannot be made too wide if one disregards the effect of rain or sunshine. If it is not needed to shield from rain or sun, then there is no reason for a roof in tropical climates. The roof is not needed just to provide a stack action effect for thermal convection. If there was no sunshine effect and no roof to hold in some of the metabolic heat because of the restrained natural wind effect, there would be no temperature differential to eliminate. A wide open ridge would, however, let in the total solar radiation with nothing to reflect and reradiate part of it. A part of the radiation absorbed by the roof is also dissipated by convection before it strikes the animal.

Question 18. What effect does grass or trees between closely spaced barns have on animal comfort and production?

Answer 18. Grass has a temperature at or below the air temperature because of its transpiration. Its reflectivity is also very low, thus it is an excellent ground cover between buildings. Grass should be trimmed regularly so that it does not harbour rodents or restrict natural horizontal winds. Trees are also advantageous if the bottom 3 m is trimmed of branches. The upper branches shade roofs from direct radiation and cut down on reflectivity. Both are advantageous.

Question 19. Does the stair-step roof produce a better environment than the conventional roof?

Answer 19. Some environmental profile measurements were run on stair-step pig barn roofs. No benefit or harm could be attributed to the additional roof openings below the ridge openings. The additional roof openings theoretically would tend to interfere with the smoothest functioning of the stack action of the ridge opening. Practically, the additional openings provide more benefit than harm by allowing more air to enter and exit as a result of natural wind forces. Any turbulence is better than smooth laminated air flow.

Question 20. How large should the ridge opening be?

Answer 20. The ridge should be 1 m wide for a 6 m wide building and each side should be open 0.5 m vertically.

Question 21. Does increasing the slope of the roof increase the total amount of solar heat absorbed?

Answer 21. Regardless of roof slope, the horizontally projected area on the ground is the same for similar sized buildings; thus, the total amount of solar radiation striking the building would be the same. Steeper roofs spread the absorption over a larger area; therefore, the solar intensity per unit area of roofing is less. This would mean a lower roof temperature if all other characteristics were the same. The steeper or sharper orientation angle of the roof surfaces with the sun would tend to cause more reflection. Also, the additional roof area and height projection would tend to provide more convective cooling from natural wind forces.

Theoretically, the inside building height should provide better stack action. However, an attempt to measure such effects in an existing barn with steep slopes did not show the expected up-flow air movement or lower temperatures. It is questionable whether the benefits would, from a practical point of view, pay for the extra construction costs.

Evaporative Cooling

Question 22. Would evaporative swamp coolers and wall pads improve animal performance in the humid climate of Singapore?

Answer 22. An analysis of the climatic conditions, 29°C and 70% relative humidity, using the psychrometic chart, indicated that evaporative cooling would provide for the evaporative losses of the animal by increasing sensible heat loss by 5% and reducing latent losses by the same amount. Evaporative cooling did not lower the enthalpy of the air; so, with both high temperature and high humidity, its benefit in evaporative loss was marginal.

The most benefit would come from the greater convective cooling capability of the air from the evaporative cooler. Lowering the temperature about 4 Celsius degrees would increase the difference between body temperature and air temperature by about 45%, which is appreciable. However, the evaporatively cooled building would only be effectively cooler if the solar radiation load was eliminated by an insulated ceiling. The question would then arise as to which was providing the most benefit.

Question 23. Will any improvement in animal comfort bring a financial return that would pay for the extra cost of evaporative cooling?

Answer 23. It is not conceivable, but there are sufficient questions to justify the development of an actual installation to check both the technical and economic feasibility of evaporative cooling.

Question 24. Would a water spray directly on the pigs be effective?

Answer 24. A water spray on the animals would be effective for the larger animals during the hottest hours of the day. An hourly body surface wetting of 1 min or less provides liquid for evaporative cooling. The wetting is a substitute for the well-developed sweat glands of humans. Wetting must only be done when the body of the pig is in need of extra evaporative cooling. In humans, the sweat glands are activated automatically when needed. Sprinkling, on the other hand, is an externally forced application.

Under no circumstances should small piglets be wetted by hose or sprinklers.

Question 25. How about using a spray or mist in front of air circulation fans?

Answer 25. In Singapore, foggers and fine sprays only raise the humidity of the already humid air and are not recommended.

Mechanical Ventilation and Cooling

Question 26. Can fans be effective in open barns and, if so, how should they be positioned?

Answer 26. Mechanical fans in open buildings should only be considered as a last resort in emergency situations. Everything else should first be done to open up the pig barns for maximum natural ventilation and to minimize radiation from hot roofing materials.

Mechanical fans are expensive and not effective, at best, in open structures. In farrowing houses, if the pens have solid partitions that are

60 cm high, as was often the case, fans are a little more effective in getting air to the sow than is natural ventilation. In one pig barn, fans were providing 1 m/s air movement 1.5 m above the floor of the pens, but only 0.1 m/s in the pens where the animals were located. Small pigs do not need the extra air, so they must be protected. Large ventilation fans that blow air horizontally the length of narrow buildings are now used in a few pig farms.

Smaller fans located higher in the buildings to blow air at a downward angle might be considered, but the area of effectiveness is very small. The slow-moving ceiling fans used in homes and public buildings could also be considered to blow air downward. Air turbulence is the major benefit.

Question 27. When should air conditioning be used and how should it be installed?

Answer 27. Mechanical air conditioning can only be considered on a zone basis. Even then, the roof or ceiling of the building must be insulated to eliminate solar radiation. Mechanical air conditioning cannot be cost effective in counteracting the radiation load.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Homeothermia: methods of body temperature regulation, zones of hypothermia and hyperthermia, and their respective critical temperatures for the local climate.
2. Principles and methods of heat loss through conduction, convection, radiation, and evaporation, and their level of importance in local climate.
3. Theoretical analyses of air movements and needs in open and closed buildings; effects of barn dimensions and construction materials.
4. Mechanical ventilation: calculation of needs, types of fans, and design procedures.
5. Analysis of recommendations for barn orientation and width; roof slope, shape, insulation, and construction materials; interbarn spacing.

Chapter 4

Pig Housing in the Tropics

This chapter highlights the major considerations in the layout and design of pig farms and pig housing facilities in hot, humid climates. It dwells on terminologies that are illustrated with figures. The opinions expressed in the question and answer section are intended to reinforce the points made in the design guidelines. The chapter was written for engineers and planners who need to know the basics of pig housing design to make decisions on waste handling and environmental matters.

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Farmlot Layout

The design of housing facilities to meet commercial pig production objectives must be based on weather conditions, local prevailing practices, constraints on land, environmental considerations, governmental regulations, and costs. It is a mistake not to [illegible] in high-quality housing designed by experienced engineers. Housi[illegible]resented approximately 5% of the total cost of pig production in Singapore; therefore, for Phase III of the Ponggol PFA, farmers had to use qualified engineers or architects to design and submit plans of the farm layout for approval.

The farm plan resulted from several trial layouts and many computations. Many functions must be performed on the pig farms, and certain factors are important when allocating space for each activity. Figure 4.1 shows a model layout of a 600-SSP farm that was designed on the basis of the Singapore experience and could accommodate an SPP of 6 000 for a PFA in Malaysia. The main components of the farm lot are: service areas, pig housing, and water and wastewater lagoon area.

Table 4.1 shows the space requirements and clearances for the various

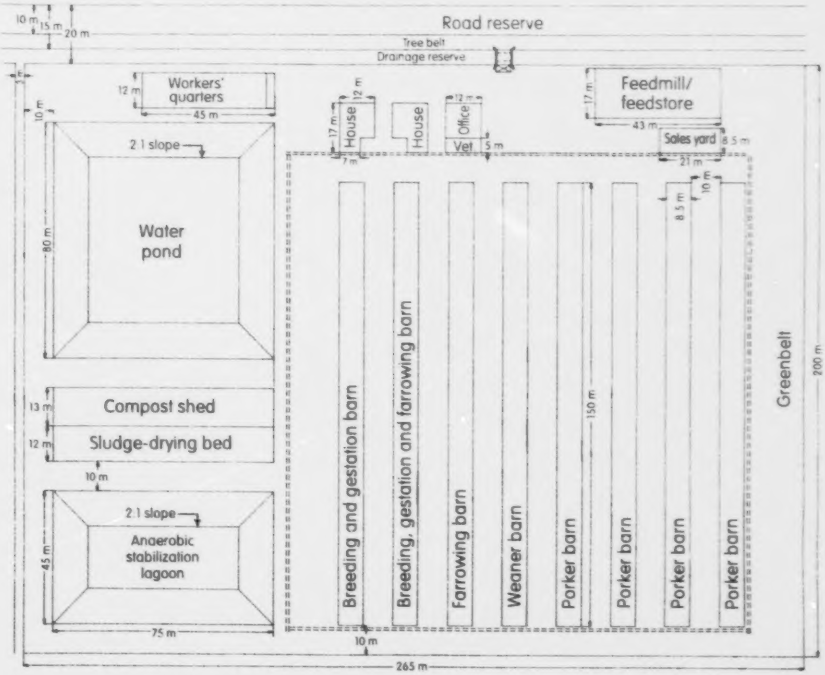
Road reserve
Tree belt
Drainage reserve
10 m
15 m
20 m
Workers' quarters
12 m
45 m
10 m
2:1 slope
Water pond
80 m
Compost shed
13 m
Sludge-drying bed
12 m
10 m
2:1 slope
Anaerobic stabilization lagoon
45 m
75 m
House
House
Office
Vet
17 m
12 m
7 m
5 m
Feedmill/ feedstore
17 m
43 m
Sales yard
8.5 m
21 m
10 m
8.5 m
Breeding and gestation barn
Breeding, gestation and farrowing barn
Farrowing barn
Weaner barn
Porker barn
Porker barn
Porker barn
Porker barn
150 m
Greenbelt
200 m
10 m
265 m

Fig. 4.1. Model farm layout. This layout was based on experience in the Singapore Phase III PFA, and was developed in Malaysia to cost and compare various options for each of the sections in the farm.

Table 4.1. Space allocation for a 600-SPP, closed-herd farm.[a]

	Min.	Design	For 600 SSP	Remarks
Services area				
Human dwellings (m^2)	200	400	400	2 family houses, 7–12 people
Worker quarters (m^2)	600	1200	1200	12–18 workers
Office and drug storage (m^2)	100	200	200	
Feed storage (m^2)	600	1200	1200	Grain bins plus mill
Sales barn (m^2)	—	—	150	100-pig capacity
Utilities (m^2)	—	—	50	
Parking and garden (m^2)	—	—	2800	Turn-around space for lorries
Gating/fencing	—	—	—	
Subtotal (m^2/SPP)	0.5	2	6000	0.5 m^2/SPP, absolute minimum
Pig housing				
Roofed area (m^2/SPP)	1.30	1.77	7800	8 m wide barns
Interbarn spacing (m)	4.0	10.0		Eave to eave from barn to barn
Interbarn spacing (m^2/SPP)	0.65	2.2	3900	Length translated into area
Barn length (m/SPP)	0.16	0.22		Based on a width of 8.5 m
Roads (m/SPP)	0.15	0.30	2700	3 m wide roads
Subtotal (m^2/SPP)	2.40	4.27	14400	2.4 m^2/SPP, absolute minimum
Waste treatment				
Lagoon (m^2/SPP)	0.62	1.50	3720	2:1 side slopes and liquid depth 5 m
Sludge drying filter (m^2/SPP)	0.15	0.20	900	Sand filter bed area
Compost and equipment area (m^2/SPP)	0.13	0.20	780	Secondary processing facilities
Access road (m^2/SPP)	0.10	0.10	600	3 m wide road
Subtotal (m^2/SPP)	1.00	2.00	6000	1 m^2/SPP, absolute minimum
Water supply and miscellaneous				
Water pond (m^2/SPP)	0.6	1.4	3600	0.6 m^2/SPP, absolute minimum
Miscellaneous (m^2/SPP)	0.1	15		Varies with final disposal of solids

[a] The values are suitable for the conditions in Singapore, where total space allocation was limited to 5 m^2/SPP. The values given for the 6 000-SPP farm are based on Fig. 4.1. The actual land-use parameters in Singapore are given in Table 4.2.

Table 4.2. Actual land utilization (%) in Ponggol Phase III PFA at different monthly population densities (MPD).[a]

	Low MPD (2.9 m²/SPP)	High MPD (8.7 m²/SPP)	Mean MPD (5.2 m²/SPP)
Services area			
Feedmill	0.53	1.45	1.24
Feedstore	0.53	4.02	2.50
Office	0.08	0.62	0.29
Dwelling	0.10	0.67	0.37
Worker quarters	0.08	0.51	0.30
Clearances and open spaces	21.07	45.29	27.00
Subtotal	32%, 1.56 m²/SPP		
Production area			
Roofed housing	27.13	35.16	32
Interbarn spacing	7.22	16.50	12
Internal roads	2.50	4.10	3
Subtotal	47%, 2.44 m²/SPP		
Waste treatment and water			
Lagoon	1.41	16.10	6
Water pond	1.49	8.15	6
Reserve	3.22	19.96	71
Subtotal	23%, 1.20 m²/SPP		
External services and buffer	1.30 m²/SPP		

[a] Data are based on actual use of the land in 1985 when 10 commercial farms in the Ponggol Phase III PFA were fully operational. The stocking density is based on the actual monthly census of SPP not on capacity. The values are based on the percentage for each of the 10 farms and thus do not total 100%.

components of a commercial-size 600-SSP, closed-herd farm for a new PFA. This was based on the Singapore experience and was proposed for pig farms in Malaysia. Table 4.2 gives the actual land-use parameters in the Ponggol PFA.

Service Area

Family Accommodations

The houses built on the Singapore farms were based on plans of typical rural dwellings prepared by the government. They were one-story wooden houses with a living–dining room, three or four bedrooms, kitchen, and patios in front and back. A few farms built concrete, two-story house compounds where several families lived, but not necessarily all family members worked on the farm. This practice was discontinued in Phase III PFA.

Workers' Quarters

Workers' quarters must have extensive shower facilities, a kitchen, a canteen, and a recreation room as well as bedrooms. Even workers who do not live in the quarters should be required to shower and change clothing before entering the pig housing area. However, these conditions were not met by any of the farms in the Ponggol PFA. These conditions were imposed, nevertheless, on farms in Malaysia, Indonesia, and Thailand that were seeking clearance to export live pigs to Singapore.

Office

Most commercial farms had offices where clerks kept production and financial records, received visitors, dispensed medicines and therapeutic drugs, and operated their computers.

Feedstore or Mill

The feedstore or mill should be located within sight of the office and have sufficient floor space to permit vehicles to enter the building. It should also be located near the electrical transformer that supplies power to the farm if feed milling is to be carried out on the farm. Most labour on a pig farm involves handling feed, and most of this feed is consumed by weaners and porkers. Therefore, the feed store should be located as close to the weaner and porker barns as possible. The connecting ways from the feed store to the barns should also allow the loaded feed carts to move downhill.

Sales Barn

The sales barn must be located at the border between the porker houses and the services area. It should have loading ramps for porkers brought from the farm for sale and unloading ramps for the porkers going to the abattoir. The sales barn should also have facilities to feed the porkers for 1–3 days so that butchers can inspect the pigs without going into the production areas.

Utilities

Provisions for telephone, electrical power, potable water, and other utilities must be approved by the necessary authorities. Their installation is covered by local rules and regulations.

Parking and Garden

Sufficient open and asphalted area must be allocated for parking and maneuvering of vehicles, particularly the heavy trucks that, in large farms, deliver feed grains. Even in small farms, there must be provision for heavy trucks to deliver formulated feeds. Some space is needed for gardening and flowers. The interfarm space should be used for landscaping with tall trees, not bushes, to promote air flow.

Interbarn Spacing

There is no doubt that, for ventilation, the further apart the buildings, the better. However, for each extra metre in interbarn spacing, there are additional costs for equal lengths of drains, wires, water pipes, and feed conveyance. In addition, pigs and workers have to walk further when animals are moved from barn to barn. The interbarn space should be no less than half the width of the barns and should be seeded in grass (no bushes) to minimize radiation loads.

Roads
Each barn must be accessible by vehicle. This was not true of the small farms in Phase I PFA; but, as mechanized feeding gained acceptance, roadways were included in the new, large commercial farms.

Clearances
Because of land constraints, interfarm spacing in Singapore was limited to 6 m eave-to-eave between barns in adjacent farms. Where land constraints do not exist, spacing of 20 m or more is advisable. The interbarn spaces should be planted with tall trees that provide shade but permit air flow near the ground.

Housing Design

Pig barns in an intensive farm are generally classified according to the stage of growth or function of the pigs.

Numbers of Pens and Stalls

The numbers of pens required for a 6 000-SPP farm are given in Table 4.3.

Table 4.3. Number of pens required for a 6 000-SPP farm.[a]

	Number of pens			
Type of pen	Min.	Max.	Suggested	Weeks
Breeding				
Farrowing pens	144	192	171	7.1
Mating pens				
Individual	48	72	64	2.7
4 per pen	12	18	16	2.7
Gestation stalls	367	426	384	16
Gilt replacement (individual)	23	35	39	10
Boar (ratio of 18:1 and 25:1)	24	33	20	52
Production				
Weaner/nursery pens (16/pen)	43	86	80	7
Porker pens (16/pen)	137	212	171	14.2
Porker production time (weeks)	22	32	27	

[a] The numbers are based on a PMY of 10 000 at 82–88 kg ALW/PMY and 1% mortality from weaning to finishing the porkers (see Chapter 2). This gives 192 weaners/week in 1 year. The pigs weaned per litter is assumed to be 8.1 per sow. The residence time in a farrowing pen is allowed to vary from 6 to 8 weeks per cycle.

Farrowing Pens

To determine the number of farrowing pens, it is necessary to decide how many litters are to be farrowed each week. There are many ways of arriving at this number. One way is to look at the number of porkers the farm is designed to produce and then determine how many piglets must be born each week to achieve that target.

For example, a 6 000-SPP farm marketing 10 000 PMY would need to have 194 piglets/week. Assuming 1% loss after weaning, the number of piglets weaned from the farrowing pen would be 192. If the number of piglets weaned per sow averaged 8.1 (see Chapter 2), then the number of litters per week would be 24, provided each farrowing took only 1 week. However, the pregnant sow is brought into the farrowing pen 1 week before farrowing, the lactation period may be 3–5 weeks, the piglets are left in the pen for an additional week, and it takes another week to disinfect the pen between farrowings. This total of 6–8 weeks means the number of farrowing pens would vary from 144 to 192 (Table 4.3). For the purposes of further calculations, the farrowing cycle is set at 7.5 weeks to allow full flexibility and allowance for irregular farrowings. The number of pens required is 180 (7.5 weeks × 24 litters/week).

Mating Pens

Sows are kept in mating pens until they are successfully mated. The average time required for sows from weaning to rebreeding is 2–3 weeks. To farrow 24 litters/week requires 48–72 mating places. Therefore, if four sows were kept in each pen, 12–18 pens would be needed.

Gestation Stalls

The gestation period is 114 days, but if the sow is moved to the farrowing stall on the 107th day, her residence time in the gestation stall is 107 days, slightly less than 16 weeks. Thus, 384 individual gestation stalls are needed (24 litters/week × 16 weeks).

To be able to move sows in groups, it is advisable to provide an additional group of sow stalls equal to the number of litters farrowed in 1 week, in this case, 24.

Gilt Pens

If the sow culling rate is 20–30%, 180 gilts need to be housed every year for an additional 10 weeks after the porkers are marketed. This would mean that 35 stalls or pens are needed.

Weaner Pens

The stocking density is assumed to be 16 SPP/pen in the weaner/nursery pens (about two litters per pen). At 194 piglets weaned per week, and because the weaners stay in the nursery pens 4–8 weeks, the number of pens needed ranges from 48 to 97.

Porker Pens

The length of stay in the porker pens depends on the weight at which the pigs are marketed. The weaners weighed about 23 kg, and would need to grow to 76–100 kg. With a daily live weight gain of 0.63 kg (4.4 kg/week), it would take 84 days (12 weeks) to reach 76 kg and 122 days (17.5 weeks) to reach 100 kg. The number of pens at 16 porkers per pen would be from 146 to 212.

Space Requirements

Space requirements change as the pigs grow and their environmental and physical needs change. Table 4.4 shows the space requirements and suggested dimensions for different kinds of pens.

Arrangement of Pens and Barns

Pig production barns should be located so that visitor traffic can be controlled or prohibited. There should be a single entrance to the pig barns, and it should be equipped with a sanitary boot wash. A separate sale area is required where butchers can buy and load porkers. The area should also have a foot wash for the butchers and a foot wash for the farm workers returning to the barns. The pig production area should be fenced for security and disease control.

Breeding Barns

When both breeding and gestation stalls are in the same barn, boar and gilt pens and mating stalls should be located at the end of the barn that is most convenient for worker access. Figure 4.2 shows a recommended layout for breeding–gestation stalls.

The mating and gestation stalls, boar pens, and gilt pens can all be put in the same barn; but, on very large farms, the owner may want to put the gestating sows in a separate barn away from the noise and activity in the mating barn. In this case, not all of the gestation stalls should be put in the gestation barn because some are needed in the breeding barn to hold sows until the pregnancy check 35 days after mating. Thus, 5 weeks of capacity, plus the extra stalls needed to move groups of sows, must remain in the mating barn.

Table 4.4. Dimensions of pens and unit costs.

Pen type	Pen cost (USD/m^2)	Area (m^2/pen)		Recommended[a]	
		Min.	Recommended[a]	Dimensions (m)	No./pen
Boar	108	7.20	7.20	3.0 × 2.4	1
Sow mating pens	108	8.64[b]	8.64	3.6 × 2.4	4
Sow stalls	108	1.44	1.44	0.6 × 2.4	1
Farrowing	146	4.32	4.32	1.8 × 2.4	1
Weaner	103	7.20	9.90	3.6 × 2.75	18–25
Porker	52	13.60	23.40	3.6 × 6.5	17–29

[a] The recommended values are based on standard 8.5 m wide barns and allow for maximum flexibility in the management of weaners and porkers.

[b] Four sows to a pen, i.e., 2 m^2/sow.

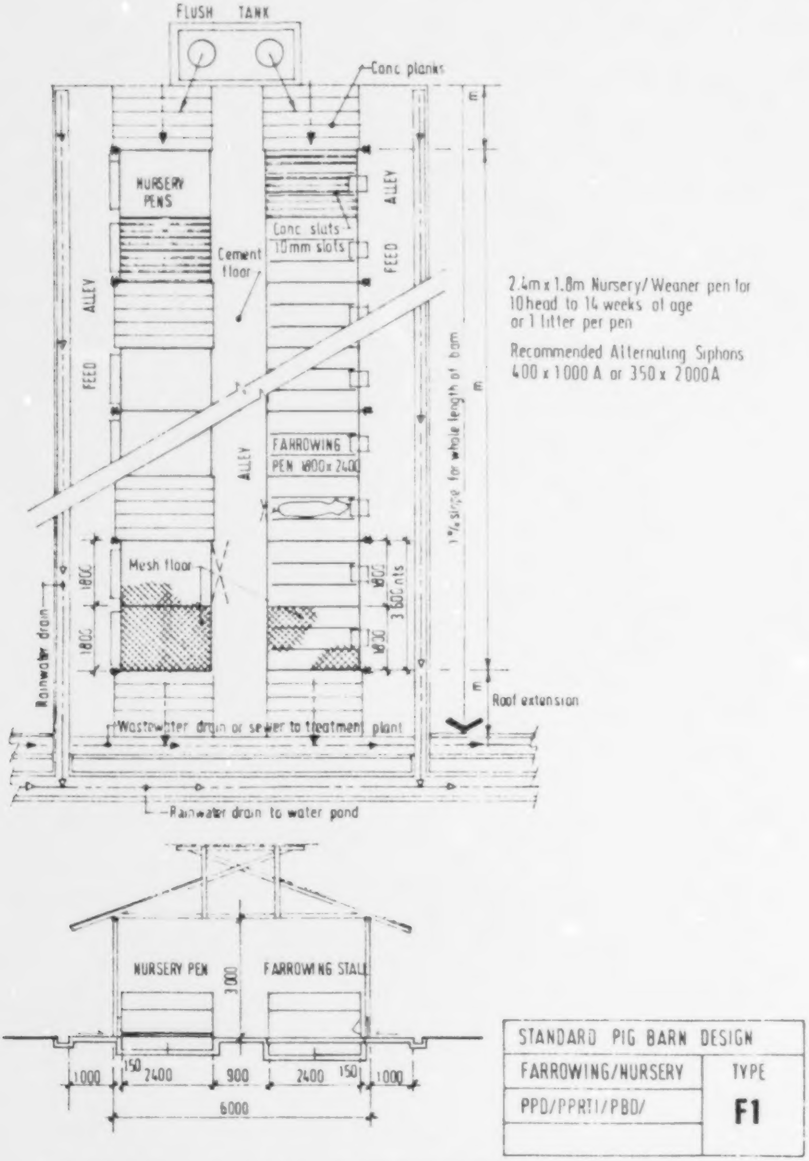
FLUSH TANK
Conc planks
NURSERY PENS
Conc slats
10mm slots
Cement floor
ALLEY
FEED
FEED
ALLEY
2.4m x 1.8m Nursery/Weaner pen for 10 head to 14 weeks of age or 1 litter per pen
Recommended Alternating Siphons 400 x 1000 A or 350 x 2000A
FARROWING PEN 1800 x 2400
ALLEY
1% slope for whole length of barn
m
m
m
Mesh floor
1800
1800
1800
1800
3 600 nts
Rainwater drain
Wastewater drain or sewer to treatment plant
Roof extension
Rainwater drain to water pond
NURSERY PEN
FARROWING STALL
3000
1000
150
2400
900
2400
150
1000
6000
STANDARD PIG BARN DESIGN
FARROWING/NURSERY
TYPE
PPD/PPRTI/PBD/
F1

Fig. 4.2. A recommended layout for breeding barns (all dimensions are in millimetres, except as indicated).

The farrowing unit should be nearest the dwelling house so that the farmers can easily check on farrowing sows at any time of the day or night. The farrowing unit should be separated from the weaner and porker unit for disease control. The breeding–gestation unit can be used to separate the farrowing unit from the weaner–porker unit.

In the layout of PFA barns, the following practical factors should be considered:

- Barns should be in an east–west direction to reduce exposure of the pigs to direct sunlight.
- The breeding–gestating and farrowing barns should be adjacent to one another to reduce the distance the animals must travel when they are moved.
- The farrowing barn should be as far as possible from human and pig traffic to reduce the spread of diseases.
- The grower/finisher barn should be located near the sale pen and feedstore, which are near the entrance of the farm (the sale pen is necessary to stop butchers from entering the production area).
- The feedstore should be located near the grower/finisher barn because these animals constitute the majority of the SPP and consume the most feed. It is also desirable to place the feedstore at the upper end of longitudinally sloping barns so that feeding will be easier if mechanical feeding systems are not employed.

Farrowing Pens

There are almost as many possible pen designs for farrowing as there are farmers. In a recommended farrowing pen, a series of vertical fingers allows the piglets much freer access to the udder without the sow being able to roll on them. The sow feeder should be large and wide and have a bar across the front to prevent the sow from nosing or pawing feed out into the pit. If feed spillage is a problem, as it was on many farms, a solid surface may need to be placed on the floor at the front of the sow. Rear entry and exit is more convenient for sow movement and allows access to the rear of the sow during farrowing and for cleaning.

Some small farms used farrowing pens that did not have rails to protect the baby pigs from being crushed by the sow. The more common old-style farrowing pen was 1.8 × 2.4 m and, generally, the only entrance to the pen was near a front corner. Also, in the old barns, there were two rows of pens back to back. In either case, there was no access behind the pen for the farmer to observe or assist the sow during farrowing.

The floors in the old barns were solid concrete or partially slatted with wood or concrete slats. Daily hosing was required to clean the pig waste from the pen, and this frequent washing chilled the baby pigs. To keep the piglets warmer, many farmers partially enclosed the farrowing barns, which created conditions that were generally too warm for the sow. It is recommended that the farrowing barn be kept open and that a protected creep area be provided for the baby pigs. Many of the farms in Phase III began to use woven wire mesh flooring to provide a drier environment for the baby pigs.

Over 90% of the waste generated in a farrowing stall falls behind the sow. The other 10% ends up in one of the four corners, most frequently one of the front corners. Some moisture is also generated under the sow's nose

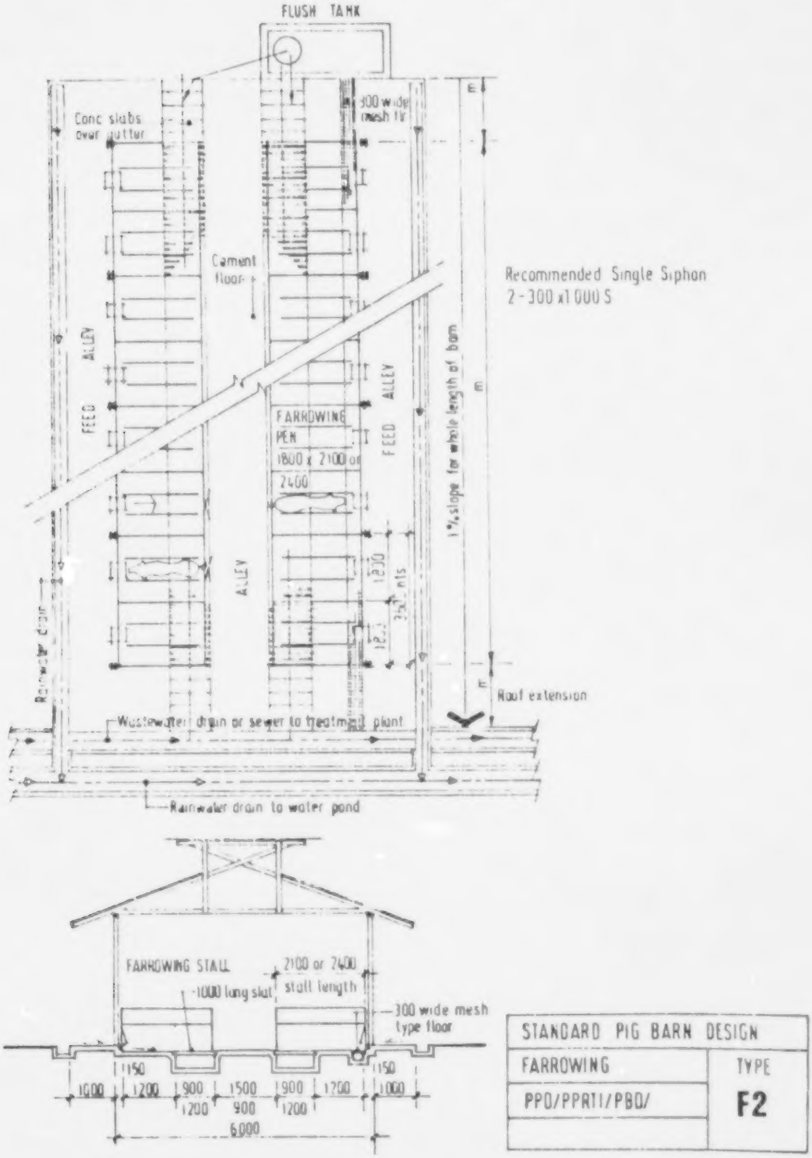
FLUSH TANK
Conc slabs over gutter
300 wide mesh flr
Cement floor
Recommended Single Siphon
2-300 x1 000 S
FEED ALLEY
FARROWING PEN
1800 x 2100 or 2400
ALLEY
FEED ALLEY
1800
1200
1% slope for whole length of barn
m
m
m
Roof extension
Rainwater drain
Wastewater drain or sewer to treatment plant
Rainwater drain to water pond
FARROWING STALL
1000 long slat
2100 or 2400 stall length
300 wide mesh type floor
150
150
1000
1200
900
1200
1500
900
900
1200
1200
1000
6000
STANDARD PIG BARN DESIGN
FARROWING
TYPE
PPD/PPRTI/PBD/
F2

Fig. 4.3. Farrowing barn with 50% slatted floor (all dimensions are in millimetres, except as indicated).

as a result of water spillage. Therefore, a slatted area is necessary only in the rear 80 cm of the pen and the front 30 cm. The centre section can be solid to decrease costs and increase sow and piglet comfort. Figure 4.3 shows a plan of a farrowing barn with 50% slatted floor area.

Proper flooring material in a farrowing stall is always a problem. The rear slats must have a high void ratio to allow the sow's manure to pass through. Yet, the slots should not be over 10 mm wide so that the piglets cannot step through and catch their legs. The flooring material must be warm and dry, and should offer good footing without being too abrasive. The material must be nonporous so that it cleans well and does not harbour bacteria. It should, of course, have a long life and yet be economical. Several of these criteria are obviously contradictory. Therefore, compromises must be made when choosing a floor material.

One of the best materials for farrowing pens is plastic-coated expanded metal or plastic-coated woven wire. Their useful life is at least 4 or 5 years. The only problem is their high initial cost. One good compromise material is galvanized woven wire mesh. It is not as comfortable and it does not provide as good footing as plastic-coated materials, but it does remove manure as well or better and cleans up well. Its useful life, however, will be less.

Concrete is one of the cheaper materials with the longest life. It is not a good choice for farrowing stalls, however, because it is uncomfortable for the pigs, abrasive, porous, and manure removal is difficult. Wood is probably the cheapest material; however, it is porous and does not clean well. Wood is much more comfortable than concrete but can be slick when wet. Galvanized flattened expanded metal is not recommended because of its short life. It is also abrasive and does not provide good footing.

For piglet comfort and survival, a heat lamp should be provided during the first 24 h of life. An alternative would be a covered box in a rear corner of the pen. An excellent idea is to construct a frame box made out of reinforcing rods. This frame is covered with a feed sack, leaving one end open, and set in a rear corner of the farrowing pen for 2 or 3 days following farrowing to serve as a pig brooder. After one use, the feed sack should be burned.

The creep divider can be cement asbestos board. This does not take up as much floor space as poured concrete or block walls and saves considerable construction labour. The initial cost is relatively high, however. An alternative would be native lumber, but it is porous, does not clean up as well, and has a shorter life.

If at all possible, sows should be farrowed in batches in small rooms. The litters should then all be removed at the same time and the entire room cleaned. For this reason, a number of small farrowing rooms with no more than 20 stalls to a room is recommended.

Nursery Pens

The concept of nursery pens for use immediately after weaning was introduced in the experimental facilities of PPRTI. The pens were the same size as the farrowing pens but had 100% slatted flooring of plastic-coated expanded metal. Each pen held two litters, but could be divided into two compartments that held one litter each. Solid panels between compartments reduce nose-to-nose contact and the spread of disease. One of the new farms in Phase III PFA used this concept, although it added to costs and management effort. Plans for a barn with both nursery and farrowing pens are given in Fig. 4.2.

Weaner Pens

The traditional weaner pens in Singapore were the same as porker pens and had solid floors that required daily hosing. Daily hosing is undesirable for weaner pigs because they chill easily when wet. The weaner pig has not yet learned where to defecate, so a 100% slotted floor is most desirable but quite expensive.

To encourage the use of better pen designs for weaner pigs, several different flooring materials (plastic-coated expanded metal, woven wire, and bare-woven wire) were imported and demonstrated at the new PPRTI barns. A double-pit design with a slatted floor in all four corners of the pen is a good compromise compared with the high cost of a 100% slotted floor. A barn with a 100% slotted floor requires much more water when twice-a-day flushing is required for odour control. Figure 4.4 shows standard plans for a weaner barn developed from the Singapore experience.

A newly weaned pig should have a clean, dry, warm environment where waste is removed as quickly as possible. The floor should be totally slatted because the small pig is not trained to use one specific area. Plastic-coated, expanded metal is probably the best flooring material; however, because of initial cost, woven wire mesh is recommended as a compromise.

For least stress and best performance, each of the pens should be divided in half, and a feeder should be placed at each end. One litter or seven or eight pigs can be placed in each pen. To save cost, but increase management, the pens can be left undivided with a feeder at only one end. With this arrangement, two litters can be put into each pen. The litters, however, should be allowed to mingle in the farrowing stall before they are moved into the nursery pen.

A 3- to 4-week-old pig needs a surrounding temperature of nearly 30°C for the first week after weaning. It is recommended, even in tropical climates, that solid partitions be used completely around the nursery pen to avoid drafts. Because small pigs are destructive, wood panels are probably sufficient, although they will not last as long as cement asbestos or plastic partitions.

Grower Pens

The pigs should be left in the weaner pens until they weigh 20–23 kg, then moved to grower pens. In Singapore, the practice was to move pigs out of the weaner pen into a porker pen, where they stayed until they reached market weight. This was an inefficient use of building space; 33%

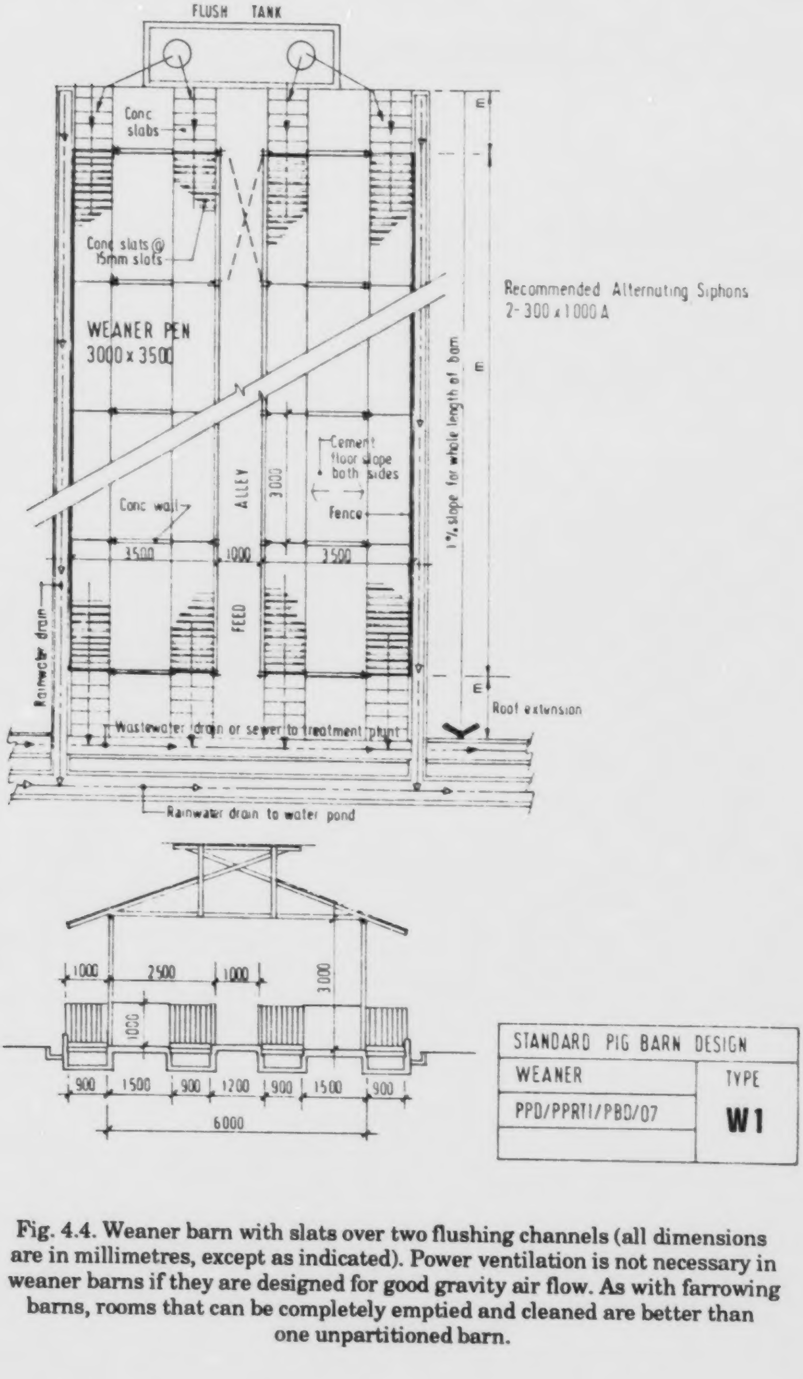
FLUSH TANK
Conc slabs
Conc slats @ 15mm slots
WEANER PEN 3000 x 3500
Recommended Alternating Siphons 2-300 x 1000 A
1% slope for whole length of barn
Cement floor slope both sides
ALLEY
3000
Conc wall
Fence
3500
1000
3500
FEED
Rainwater drain
Wastewater drain or sewer to treatment plant
Roof extension
Rainwater drain to water pond
1000
2500
1000
3000
1000
900
1500
900
1200
900
1500
900
6000
STANDARD PIG BARN DESIGN
WEANER
TYPE
PPD/PPRTI/PBD/07
W1

Fig. 4.4. Weaner barn with slats over two flushing channels (all dimensions are in millimetres, except as indicated). Power ventilation is not necessary in weaner barns if they are designed for good gravity air flow. As with farrowing barns, rooms that can be completely emptied and cleaned are better than one unpartitioned barn.

more building space was required because there were often far too few pigs per pen. It is much better to put the pigs into smaller grower pens and then, half way through the growth period, move them into larger finisher pens. Some additional labour is required, but this system saves considerable labour in pen washing because too few pigs in a large pen contributes to poor dunging patterns. Pens are much harder to keep clean if the pigs are not encouraged to train themselves properly. Sufficient animal density is one of the primary ways to train pigs.

Porker Pens

The traditional porker pen had a sloping solid floor, which required daily hosing to remove waste and clean the pigs. The pen was nearly square because a long feed trough was required for manual feeding. To accommodate this type of pen design and allow for automatic flushing and feeding, a new barn plan was developed (Fig. 4.5).

To minimize water use for cleaning, the concept of putting slatted floors at both ends of the weaner and porker pens was introduced (Fig. 4.6). It has long been recognized that pigs will most frequently defecate in a corner of a pen; this layout includes slatted flooring in each corner of the pen. This design required that the self-feeder be in the centre of the pen and be filled by a mechanical conveyor. The pen also reduced the frequency, labour, and water required for washing the pigs. Pen hosing was reduced from twice a day to once every third or fourth day. About 50% of new weaner and porker barns constructed after this concept was introduced were of this type.

As an alternative to slatted floors, an open-gutter porker pen was also tested in Singapore. Plans for a porker barn with open-gutter flushing are shown in Fig. 4.7.

The first farm built in the Ponggol Phase III PFA in 1981 accepted the open-gutter flushing design. For best results, it was recommended that the open gutter be flushed by automatic siphon hourly during daylight hours to entice the pigs to defecate and urinate in the gutter. Because the waste-treatment plant was not yet built, the gutter was flushed only once daily; therefore, the effectiveness of the system was not fully tested. The farmer had to wash the pens; however, most pig dung fell in or near the open gutter, so the time and water required for hosing was much less than for the old-style, solid-floor barns. As recommended, the pigs in these pens were fed on the floor, which encouraged them to defecate in the gutter.

Gestation Barns

A study of the gestation stalls used in Singapore found them to be adequate and trouble-free. The sows were placed into 60 cm wide stalls with a section of concrete slats toward the rear. Hand feeding was practiced on small farms. On larger farms, mechanical feeding was introduced after 1981. Good management required that someone walk through and check every sow every day.

Figure 4.8 shows plans for a breeding–gestation barn. The sows face out, so their heads receive better ventilation. This plan also allows for

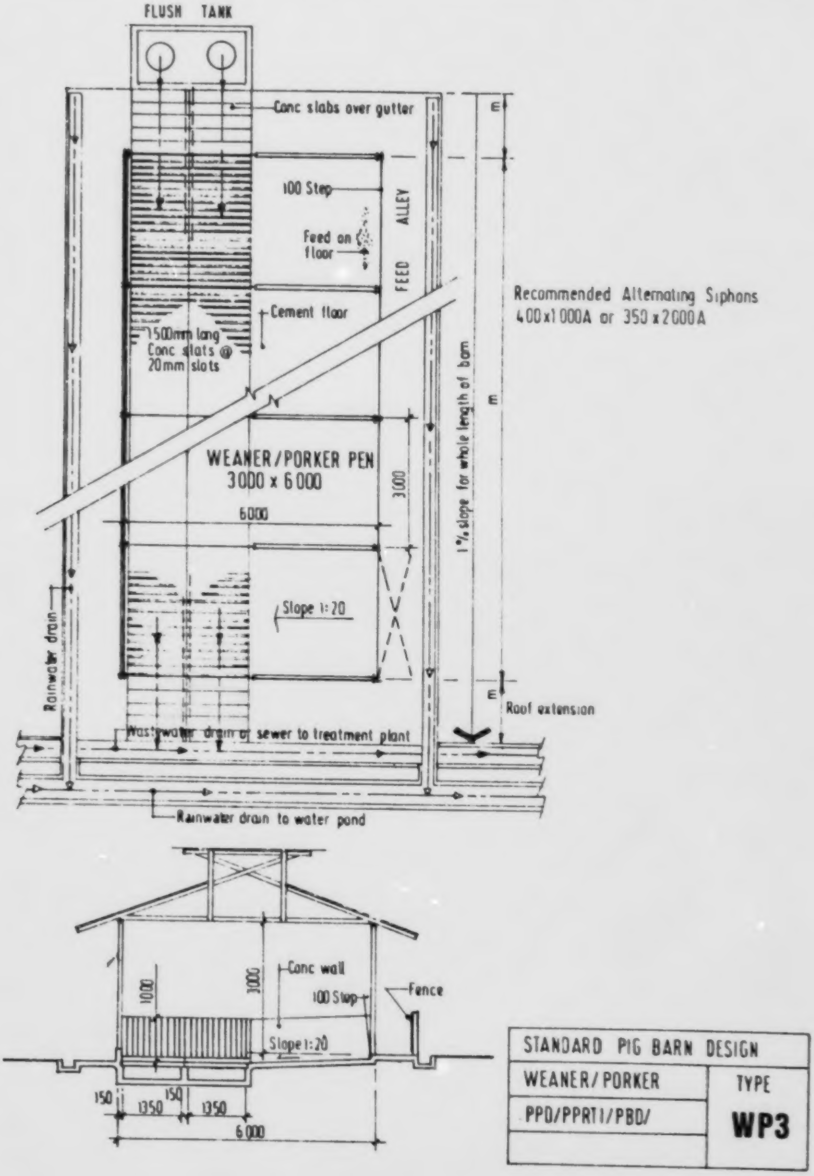
FLUSH TANK
Conc slabs over gutter
100 Step
Feed on floor
FEED ALLEY
Cement floor
1500mm long Conc slats @ 20mm slots
Recommended Alternating Siphons 400x1000A or 350x2000A
WEANER/PORKER PEN 3000 x 6000
6000
3000
1% slope for whole length of barn
E
Slope 1:20
Rainwater drain
Roof extension
Wastewater drain or sewer to treatment plant
Rainwater drain to water pond
Conc wall
1000
3000
100 Step
Fence
Slope 1:20
150
1350
150
1350
6000
STANDARD PIG BARN DESIGN
WEANER/PORKER
PPD/PPRTI/PBD/
TYPE
WP3

Fig. 4.5. Weaner–grower–porker barn with sloped floor (all dimensions are in millimetres, except as indicated). Grower pens should have 0.5 m^2 of floor space per pig. For good performance, and to discourage such problems as tail biting, no more than 25 pigs should be put in one pen.

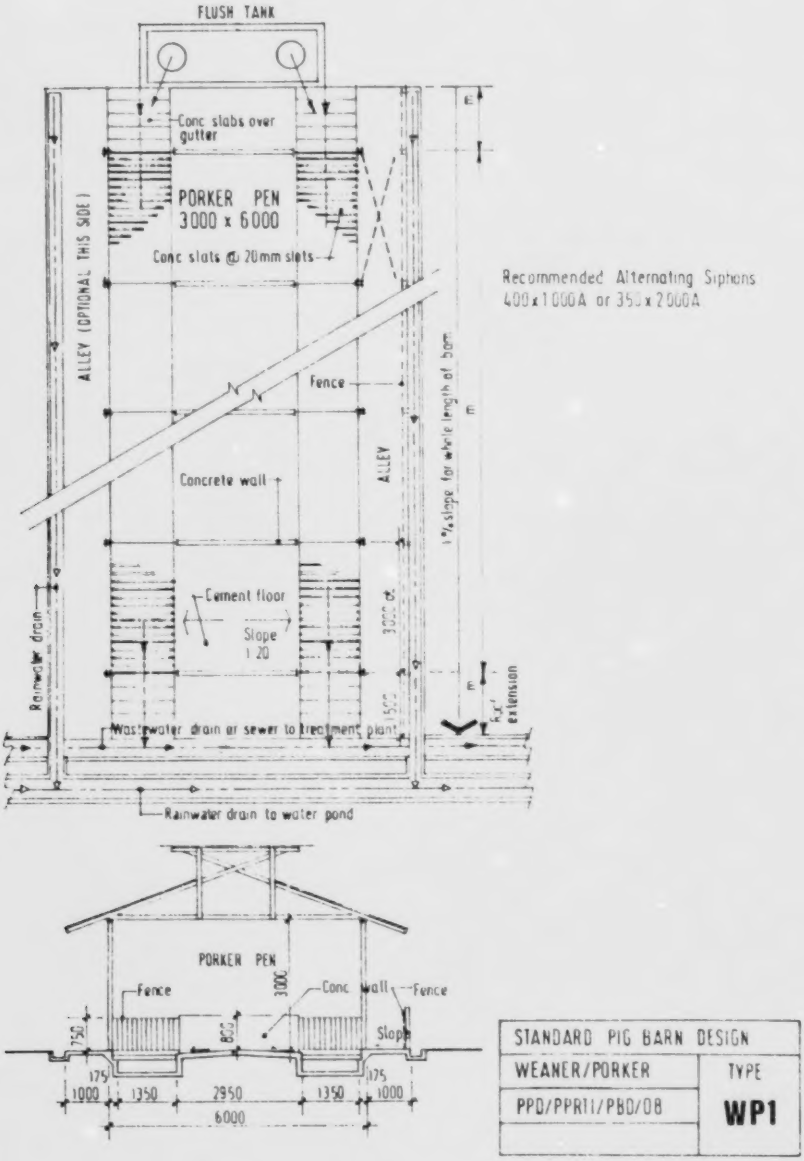
FLUSH TANK
Conc slabs over gutter
PORKER PEN 3000 x 6000
Conc slats @ 20mm slots
ALLEY (OPTIONAL THIS SIDE)
Recommended Alternating Siphons 400 x 1000A or 350 x 2000A
Fence
Concrete wall
ALLEY
1% slope for whole length of barn
E
Cement floor
Slope 1:20
3000 ct
1500
Rainwater drain
Wastewater drain or sewer to treatment plant
Fut. extension
Rainwater drain to water pond
PORKER PEN
Fence
3000
Conc wall
Fence
750
800
Slope
175
1000
1350
2950
1350
175
1000
6000
STANDARD PIG BARN DESIGN
WEANER/PORKER
TYPE
PPD/PPRII/PBD/08
WP1

Fig. 4.6. Weaner to porker barn (all dimensions are in millimetres, except as indicated). This concept was first implemented on the industrial farm, where five barns were built in 1982 and 1983. Each barn was 282 m long and contained 1 800 porkers.

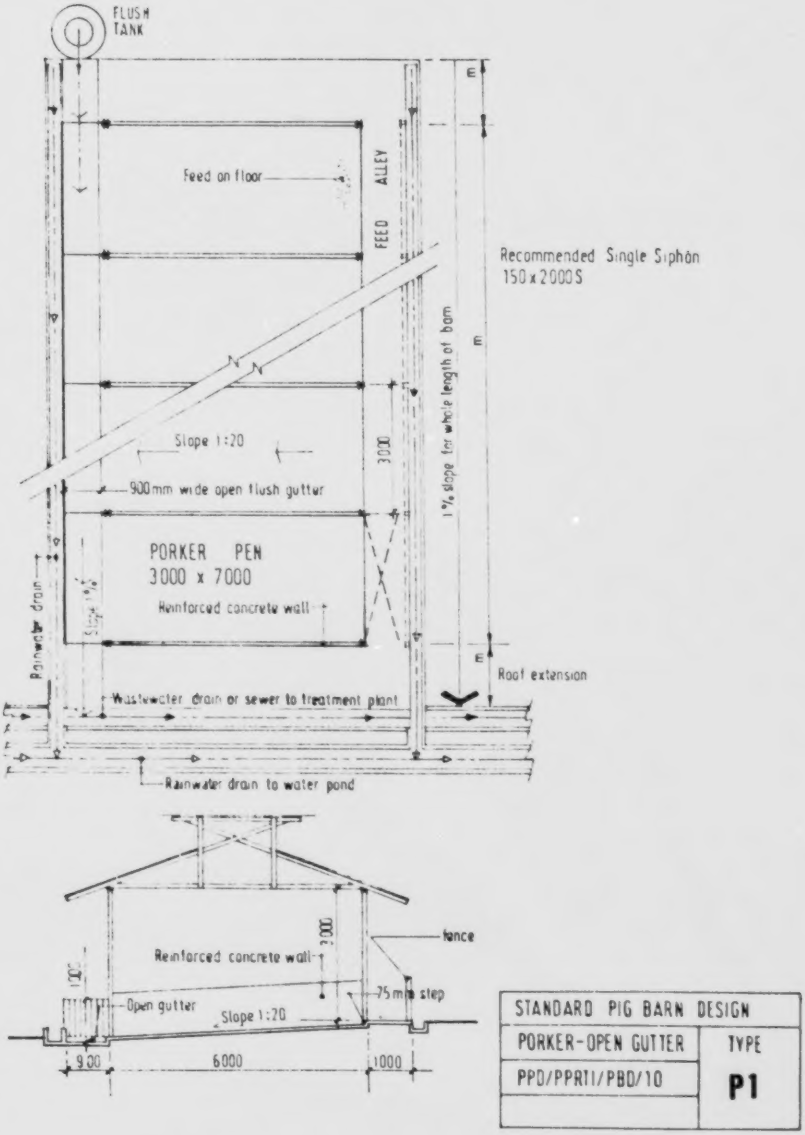
FLUSH TANK
Feed on floor
FEED ALLEY
Recommended Single Siphon
150 x 2000 S
1 % slope for whole length of barn
m
m
m
Slope 1:20
3000
900mm wide open flush gutter
PORKER PEN
3000 x 7000
Reinforced concrete wall
Slope 1%
Rainwater drain
Roof extension
Wastewater drain or sewer to treatment plant
Rainwater drain to water pond
fence
2000
Reinforced concrete wall
1200
Open gutter
Slope 1:20
75 mm step
900
6000
1000
STANDARD PIG BARN DESIGN
PORKER-OPEN GUTTER
TYPE
PPD/PPRTI/PBD/10
P1

Fig. 4.7. Open-gutter flushing porker barn (all dimensions are in millimetres, except as indicated). This system was tried in the experimental barns at PPRTI. During hot weather, the pigs tended to lie in the gutter and impede the flow of the flushing water. No disease problems were encountered, however.

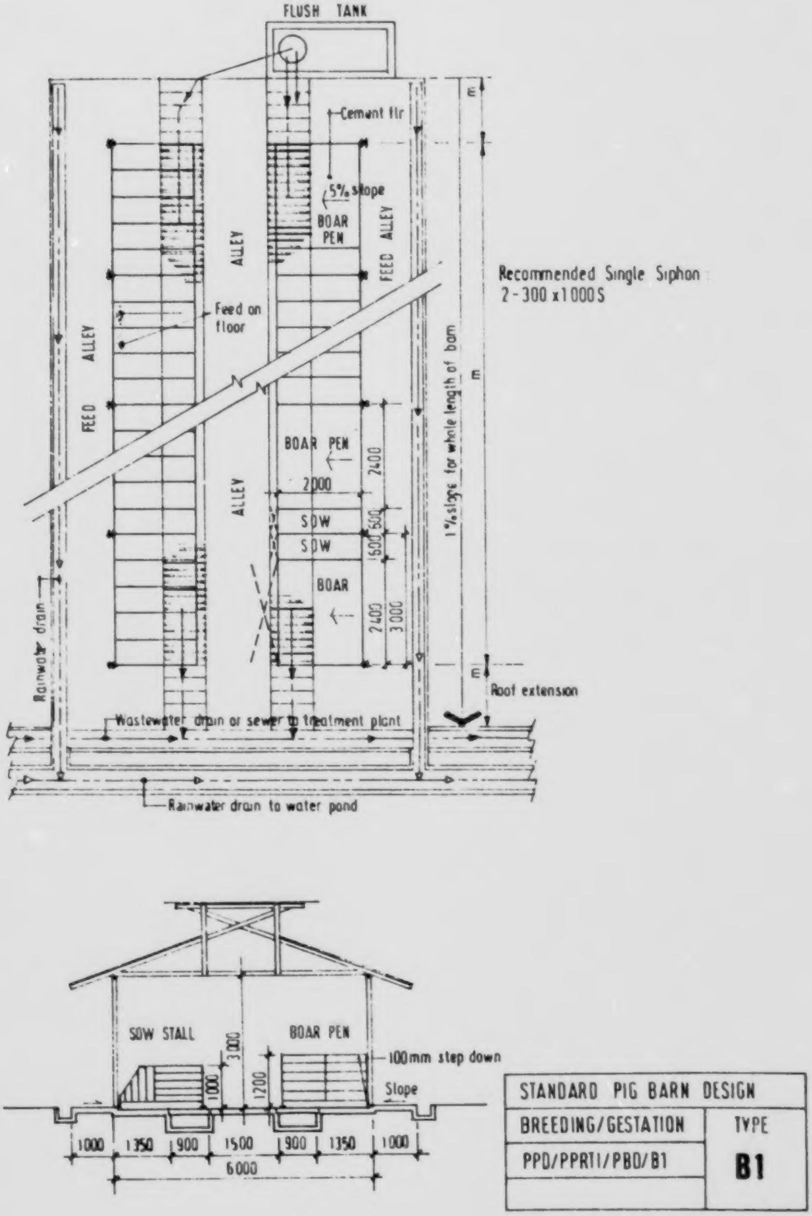
FLUSH TANK
Cement flr
5% slope
BOAR PEN
ALLEY
FEED ALLEY
Recommended Single Siphon
2-300 x 1000 S
Feed on floor
FEED ALLEY
m
m
m
BOAR PEN
2400
2000
ALLEY
SOW
SOW
600
1600
BOAR
2400
3000
1% slope for whole length of barn
Rainwater drain
Roof extension
Wastewater drain or sewer to treatment plant
Rainwater drain to water pond
SOW STALL
BOAR PEN
3000
100mm step down
1000
1200
Slope
1000
1350
900
1500
900
1350
1000
6000
STANDARD PIG BARN DESIGN
BREEDING/GESTATION
TYPE
PPD/PPRTI/PBD/B1
B1

Fig. 4.8. Plans for a breeding–gestation barn (all dimensions are in millimetres, except as indicated).

better sow movement and breeding in the centre alley. Boar pens can be spaced anywhere in a row of sow stalls for best breeding efficiency. Farmers made sow stalls with solid, high-tensile, concrete reinforcing rods that seemed to last longer than pipe or tubing.

On older farms in Singapore, the sows were often kept in pens measuring 1.2 × 2.4 m. These pens took twice as much space as needed and, because they were large, the sows could turn around and dirty the entire floor area. Individual feed troughs were introduced when the farms installed mechanized feeding.

Boar Pens

For every 10 stalls, there should be a boar pen in the breeding area. Breeding can then take place both in the boar pens and in the aisles.

Aisles

The aisle width should be sufficient to allow free movement of feed trolleys and of animals.

Other Facilities

The other facilities that need to be included in the plans are pipelines for the supply of drinking water, a hosing network for pen cleaning, electrical wiring, water storage tanks, feed storage bins, and feed conveyance mechanisms.

General Construction Guidelines

Farm Components

Modular Construction

A building module length should be selected that can be used throughout the pig barns. A 3.6-m post spacing works for all barns.

Roofed Area

The roofed pig housing area of pens and alleys, and covered lanes on both sides of the barns, must not be less than 1.4 m^2/SPP and no more than 1.77 m^2/SPP. A uniform roof width will minimize construction cost. A width of 6 m from post to post will work for all barns. A roof overhang of 1.2 m at the sides and ends is recommended.

Interbarn Spacing

The distance between barns cannot be less than 4 m and no more than 10 m from eave to eave, unless otherwise dictated by topography or other reasons.

Interfarm Spacing

The distance from the eave of a pig barn to the eave of a barn in a neighbouring farm must be no less than 20 m and preferably 40 m.

Clearances

In addition to honouring the reserves and easements required by government authorities, a clearance of at least 3 m must be maintained between buildings and farm fences.

Greenbelt

Trees (decorative, fruit, or plantation, but no bushes) should be planted in the 3-m reserve along the fence perimeter and in the interfarm or interbarn space. Large trees should be planted about 15 m apart.

Water Pond Reserve

Each farm must have a water pond that will provide a minimum of 100 days of water storage unless adequate provisions are made for the regular supply of such water via centralized supply systems, wells, or other means. The area reserved for water storage should collect surface waters from the barns and the interbarn spaces, irrespective of the size of the farm.

Waste Area Reserve

An area of at least 1 m^2/SPP must be provided for the collection and on-farm treatment of wastes and wastewaters, and must collect by gravity the total wastewater flow of the entire production area of the farm.

Solids Utilization Reserve

If available, an area of at least 7 m^2/SPP is needed for the storage and disposal (as landfill) of dried sludge solids (more than 20% TTS, i.e., less than 80% moisture content). Acceptable alternatives are disposal on plantations of fruit trees, fodder, or other crops or trees that can be commercially cultivated or harvested.

Internal Services

An area of at least 1 m^2/SPP should be reserved on each farm for internal services. This area must be within the farm fence perimeter but must be fenced out of the production area. It must include an entrance with proper wheel disinfection and sprinkler equipment for vehicles, a walkway, an office, veterinary drugs storage and dispensary, a sales yard, feed storage and processing, family housing, worker quarters and related facilities, a parking area, and an animal carcass bin.

Construction

The supporting posts and roof should be constructed first so that work on floors, pits, and pens can proceed during the rainy period or adverse weather.

Barn Layout

Orientation

Unless absolutely impossible because of topography or other reasons, pig barns should be oriented in an east–west direction to minimize direct sunlight on the pigs.

Dimensions

Barns should be 8–9 m wide. The buildings should be long enough to accommodate all the farrowing pens (or to house all the weaners). This would provide for maximum husbandry care without exposing piglets (the most vulnerable animals) to other animals and workers.

Floors

All floors must be concrete. The floors should be at least 100 mm thick, even beneath slatted flooring. The use of steel reinforcement bars or mesh in solid slab floors at grade level is generally a waste of money in livestock buildings. Slatted floors are recommended to minimize water usage for pig bathing and floor washing, provided adequate provisions are made for the hydraulic removal of the fecal droppings. No dirt floors should be permitted in any barn area. Manufactured precast concrete slats are preferred to farm-made slats because they are more uniform and durable, and have reliable design loadings.

Roofs

Barn roofs should have a minimum slope of 20° and must have a covered ridge opening (1.2 m wide and 0.6 m deep, minimum) along their entire length. Provisions must be made to collect rainwater from the roofs with gutters or concrete drains along the eaves of the barns.

Floor Designs

Concrete Floors

A floor slab 100 mm thick is sufficient. There is no need for reinforcement. The floor should slope 4–5% (1:20 to 1:25) toward the waste-collection drain or slatted area.

Slatted Floors

Concrete slats are the most common and durable. Other materials that can be used are fibreglass or plastic and flattened, expanded metal (galvanized).

On most farms, too little of the pen area was slatted and there was too little space between slats. Therefore, daily hosing of the pens was needed to break up the feces and push them through the slats.

To make good concrete slats, experienced workers and proper equipment are required to measure and mix the concrete accurately. It is not advisable to make concrete slats on the farm. Poor-quality concrete deteriorates faster when exposed to acids in animal manure and, as the edges of the slats break off, foot problems begin to occur in the pigs.

The slats require a ledge at the top of the pit walls for support. This ledge should be at least 50 mm wide for slats up to 1 m long. For longer slats, the ledge should be 75 mm wide. The length of the opening across the pit should be 10–20 mm longer than the precast slat to make placement easier. At the end of a pen, where the slats are parallel to a pen wall, a space of 50–75 mm should be left between the last slat and the wall. This allows waste to fall into the pit rather than accumulate on that last slat.

Floors in the pen adjacent to the slats should be sloped toward the pit at 1:20 to 1:25 (4–5%) so that moisture and feces will move toward the slatted area. Another helpful detail for weaner and porker pens is to use a small step (25–50 mm) to prevent pig waste balls from rolling off the slatted floor onto the solid portion. However, no steps should be installed in farrowing pens, gestation stalls, or boar pens.

Concrete slats are installed with a mixture of sand and cement (grout) to anchor and space the slats. The grout surface should be smoothed with a steel tool so that waste will not accumulate. A concrete cove should also be placed along the walls. This prevents the accumulation of waste, because there is usually not enough foot traffic by the pigs to push the waste into the pit. The cove may be precast concrete or made from a grout mixture and trowelled into placed after the slats are set.

Flooring Materials for Farrowing and Weaner Pens

There is a plethora of flooring materials and products. Because of the sensitive needs in farrowing and weaner pens, the suitability and life span of these products must be considered carefully.

Concrete Slats

Use of concrete in farrowing pens should be carefully assessed. Concrete is a cold material that will conduct body heat away from the piglets. Farm-made concrete slats may also lack the fine finish necessary in farrowing stalls to prevent knee abrasions in nursing piglets. The top surface of concrete slats tends to be concave and hold considerable amounts of manure and moisture, creating a bad environment for the young piglets. Concrete slats have the longest life, but it is difficult to get a good concrete finish unless they are cast upside-down.

Wood Slats

Slats should only be made of hardwood that have adequate strength. However, even hardwood absorbs moisture and does not clean easily. Therefore, it provides an excellent place for bacteria to grow, transmitting disease to successive groups of pigs. Although wood slats are the cheapest to build, their life span is short. It is also difficult to maintain proper spacing because wood slats tend to warp.

Plastic Slats

Plastic slats clean easily and feel warm to the piglets; however, they are slippery, especially parallel to the length of the slat. The cost of all-plastic flooring is high.

Expanded Metal

Regular expanded metal offers excellent footing, but the sharp edges of the "up-turned" steel are harmful to knees and abrasive to hooves. The life span of bare expanded metal is short because of the corrosive nature of the wastes. It is not recommended.

Flattened Expanded Metal

Flattened expanded metal is abrasive to the feet of the piglets and is equally dangerous to sow teats. Teats can get caught and cut off in the diamond shaped openings, and piglets' legs can be scraped. This material is not recommended for farrowing stalls, but can be used in weaner pens, although its life is short. Galvanized metal will last longer if it is galvanized to an adequate thickness (600 g/m^2).

Welded Wire Mesh

Welded wire mesh is typically made of parallel wires 10 mm apart with cross wires spaced at 30–50 mm. It gives the piglets poor footing parallel to the main wires, but it is always dry.

Woven Wire

Woven wire will flex as the pigs walk on it, which helps work the manure through the floor. The woven texture gives good footing in both directions and is always dry. It can be made from galvanized or stainless steel wire.

Plastic-Coated Expanded Metal

Plastic coating reduces the cold feeling of expanded metal and gives a good nonabrasive surface for the piglets to walk and lie on. It is always dry. Plastic cleans easily and protects the metal from corrosion. Good-quality products are guaranteed for 5 years. If the metal is not flattened, the weight of the sow forces the plastic coating down over the sharp edges of the upturned expanded metal and cuts the coating from the inside. The use of a flattened expanded metal base eliminates the sharp edges and provides a more comfortable surface to lie on.

Plastic-Coated Welded Wire Mesh

Plastic coating improves the characteristics of plain welded wire. It is always dry.

Plastic-Coated Woven Wire

Plastic-coated woven wire loses some of its flexibility and, thus, its advantage in working the manure through the floor. It makes a better floor than plastic-coated welded wire mesh because it provides better footing in both directions.

The plastic coating is produced by one of two methods. The original method was to dip sheets of metal into the plastic and air-cure the plastic coating. Manufacturers who use this process give only a 1- to 2-year warranty on their product because the plastic coating is soft. In the second process, the plastic coating is baked in an oven. This gives a much harder, more durable coating and a longer useful life. Manufacturers who use the baking process give warranties of 5 years or more.

Recommendations

For farrowing stalls and nursery decks, the order of preference for floor material is as follows:

- First, plastic-coated, baked-on, flattened expanded metal with a finished opening size that allows a 10-mm ball to pass but not a 13-mm ball.
- Second, plastic-coated, baked-on, woven wire with a finished opening that allows an 8-mm but not a 12-mm ball to pass through (length of openings not to exceed 50 mm).
- Third, woven wire, stainless steel, with openings that allow an 8-mm but not a 12-mm ball to pass (length of openings not to exceed 50 mm).
- Fourth, concrete slats with smooth edges cast upside-down.

PFA and Housing Costs

The general guidelines detailed here, along with waste collection, treatment, and recycling plans, were used to design 10 commercial farms in Ponggol Phase III PFA. Because the PFA site was developed by the government and architectural plans were prepared both for the PFA and for the individual farms, costs could be determined. Costs of materials and construction vary with location and from year to year. Nevertheless, the values presented are useful sample calculations and guidelines for future development of integrated pig farming areas under severe land constraints. Because unit costs are included, the data can be updated using formulas or current local unit-cost data.

Table 4.5. Cost of land acquisition and development for PFA.

	Phase I	Phase II	Phase III
Years of development	1974–1975	1975–1976	1980–1983
Area of PFA (ha)	208	253	189
Area in actual pens (ha)	71	42	161
Land acquisition in 1975 (USD/ha)	20566	20566	20566
Squatter compensation (USD/ha)	5752	14434	21347
Subtotal, land costs (USD/ha)	26318	35000	41913
Infrastructure costs (USD/ha)	3843	4368	16816
Potable water supply (USD/ha)	1773	1425	521
Electrical cabling (USD/ha)	—	—	1062
Substation/street lighting (USD/ha)	—	—	988
Road network (USD/ha)	—	—	2231
Costs after acquisition (USD/ha)	5616	5793	21600

PFA Costs

Table 4.5 shows the total costs of developing the land that had been zoned as PFA during the three phases of its development for commercial production. The land-development costs of 21 600 USD/ha in the Phase III PFA were charged to the farmers at an annual rental rate of 3 300 USD/ha. At a stocking density of 5 SPP/m^2 or 2 000 SPP/ha, the annual land cost amounted to 1.65 USD/SPP or 1 USD/PMY at an annual extraction rate of 1.65 PMY/SPP.

The costs for the Government of Singapore to acquire the land, which was held privately, survey it, design the PFA lots, clear the land, and build a utilities and drainage network constitute the "infrastructure" costs. After acquisition, the land became government property and was eventually to be used in New Town residential development. Therefore, the extensive land-forming costs were justified on the basis of the eventual use of the site. All costs were passed on to the commercial farmers who leased their lots at an annual rate of 3 300 USD/ha. The small farmers used the lots on a temporary occupation licence that had to be renewed every year at a nominal cost. Even the small farmers were compensated when the government phased out pig farming.

The increased costs for Phase III are due to inflation (which, in Singapore, was low before 1981), but mainly the extensive earthworks necessary to level off the hills that existed, fill the low swampy areas, and achieve the 1% grade that was necessary for the flushing systems. An electrical substation also had to be built to supply the high energy requirements of the feed mills and waste-treatment plants. Water supply was less expensive in Phase III because the mains were installed under Phase I. Roadways that could handle 10-t trucks were built in Phase III, along with large, concrete drainage canals. The 7.4-m roadways were lined with tall trees, while the PFA border with Ponggol Road was planted with thick bushes to block the view of the pig farms from the houses on the west side. Table 4.2 presents the land utilization figures for the PFA.

Housing Costs

The farms in Phase III were required to use licenced architects and engineers to prepare their farmlot layouts and barn designs. Thus, it was possible to extract from the detailed drawings the quantities of material needed for individual housing units, pens, feedmills, etc. The prices quoted by contractors were available, so the cost of construction and operation could be calculated. When pig farming was phased out by government decree, the farmers had to be compensated for their investments. It was necessary, therefore, to obtain actual costs from the farmers themselves and compare them with those estimated by government surveyors and engineers.

The cost of housing units was based on quantitative surveys of the materials and services needed to build the substructure, the superstruc-

Table 4.6. Actual and calculated costs for pig housing.[a]

	USD/ pen	USD/ m^2	Min. (USD/ 600 SSP)	Max. (USD/ 600 SSP)	Design			
					Pens	USD/ 600 SSP	USD/ SPP	%
Breeding								
Farrowing	636	65	91584	122112	171	108756	18.1	23
Gestation	155	55	56885	66030	384	59520	9.9	12
Boar	774	55	18576	25542	20	15480	2.6	3
Porker production								
Weaner	1003	53	43129	86258	80	80240	13.4	17
Porker	1265	55	173305	268122	171	216315	36.1	45
Total	—	57	383479	568122	—	480311	80	100
USD/SPP	—	—	64	95	—	80	80	—
USD/SSP	—	—	640	950	—	800	—	—
Range of costs								
USD/SPP			50–60	55–108				
USD/SSP			500–600	550–1080				

[a] The actual costs are those estimated by the farmers when they built the new types of buildings between 1981 and 1983. The calculated costs are based on quantitative surveys of materials and services from detailed construction drawings and unit prices charged by contractors. The minimum and maximum are based on the number of pens required (see Table 4.4) and the management and husbandry practices of the farms. The cost is per square metre of roofed building area for each type of barn (USD/m^2).

ture, walls, fixtures, roofs, and metal and plumbing work. The costs of all barns and pens are summarized in Table 4.6.

The actual costs to the farmers in terms of cash paid may have been less than those shown in Table 4.6. The farmers should have been able to procure the materials themselves at a 5–10% discount, provide some of the labour themselves, and save on the contractor's profits. Their costs ranged from 50 to 108 USD/SPP. On average, the cost of establishing the housing component of a commercial farm in the tropical conditions of Singapore was less than 1 000 USD/sow. In the closed-herd farm, 38% of cost was for the breeding part and 62% was for the production of porkers.

Questions and Answers

Pen Design

Question 1. Should the slat spacing directly behind the sow in a farrowing pen be 2.0-2.5 cm instead of the 1.0 cm used in rest of the stall?

Answer 1. This question is applicable if concrete or wood slats are used, but these are not recommended for farrowing pens. If wire mesh is used, no different spacing is required because the mesh tends to self-clean much better. However, if a producer feels that the sow manure is causing a problem, a small section of slats at the rear of the stall should be removable. This section could then be picked up and the sow manure scraped into the gutter. This works better than wider slats behind the sow because the slats which have to be covered during the lactation period after farrowing.

Question 2. Most of the existing farms had large farrowing houses with more than two rows of pens. Is it possible to have batching and all-in all-out systems by using partitions in such houses?

Answer 2. In the large, wide farrowing houses, as they were built in Phase I, it would be very difficult, if not impossible, to divide them into small rooms for batch farrowing. In the narrow, two-row configuration, a partition would be placed about every 12 to 15 m. This partition could be constructed of thin plywood and be 2–3 m high. The main purpose of the partition is to prevent air and water movement between the sections, especially during cleaning.

Question 3. It is recommended that a creep box made of burlap be used in the farrowing pens for the baby piglets, which require 35°C temperatures. Would it be better to make this box with transparent material, such as plastic, on the top so the farmer could observe the piglets? Is it true that piglets might prefer to use this box because they tend to avoid dark areas?

Answer 3. In the United States, creep boxes are often used in conjunction with heat lamps. They nearly all have hinged tops to provide access to the pigs. In tropical climates, the heat lamps may be eliminated if a covered creep is used. In a pig environment, dark is usually associated with cool. This is why piglets tend to avoid dark corners. If the brooder is warm and comfortable, the pigs will use it when they need to, even if it is dark. It is important to have access to the creep to observe the pigs. Therefore, a solid creep cover should be hinged. The burlap bag idea has several advantages that compensate for the lack of access. No one method is ideal.

Barn Width

Question 4. Is an 8 m wide building the most efficient size for two rows of farrowing stalls, gestation stalls, or nursery pens?

Answer 4. Not necessarily. An individual producer would design and build a slightly narrower building with narrower aisles. The savings would not be great. The building width suggested was a compromise for all uses to arrive at a standard building size in a PFA. A standard building is useful if a single detailed construction plan is to be used by all builders. If individual producers had their own plan drawn, they could vary the building width to improve the use of building space. It must be kept in mind that a wide aisle is not necessarily a waste of space, especially in buildings where hand feeding is recommended.

Question 5. What are the merits of making the finishing porker barn double width and installing a centre flushing gutter?

Answer 5. In this specific circumstance, an exception could be made to the narrow building. With the gutter in the centre of the building and the sleeping–eating area toward the outside, two pens could be put back to back under the same roof. The ridge opening would need to be expanded in proportion to the width, and the height increased to maintain the same roof slope. The minimum distance between buildings would have to be increased to at least twice the ridge opening size. With these changes, a double wide building would work as well as the single width arrangement for finishing animals.

Question 6. Could the nursery building be decreased in width by adding automatic feeding? Would the decrease in building size plus the labour saving pay for the automatic equipment?

Answer 6. The aisle width could probably be decreased in the weaner building if feed handling were automated. Nevertheless, the savings would be relatively small. Automated feeding in the nursery, however, is not highly recommended. First, the quantity of feed is not large and the labour time is not long. Second, someone needs to observe the condition of the small pigs every day and note how much they are eating. This can best be done while feeding the pigs manually.

Weaner Pens

Question 7. There is an increasing interest in decking for weaner pigs. Is it applicable in tropical climates?

Answer 7. Interest in multiple decking of weaner pigs has peaked in the United States and Europe. A few ardent supporters, especially those with existing decked facilities, are still recommending it. However, the idea is no longer growing. The idea gained impetus because two or three times the number of pigs could be put in the same building. It soon became apparent, however, that ventilation problems increased in proportion to the number of decks.

Moreover, significantly increased labour and management skills were also needed. Getting the pigs in and out of the pens was difficult and laborious. It was also much more difficult to observe the condition of the weaner pigs. Potential disease problems were enhanced. For these reasons, but particularly because of the ventilation problems, multiple decking would not be practical in the tropics.

Single raised decks are different. In the United States, weaner pigs in some farms are raised onto slatted decks to get them away from contact with the cold floor and into the warm-air region of the building. This appears to increase performance and decrease disease incidence. In Singapore, however, warmer ground and air temperature make it unlikely that similar results would be obtained. Therefore, the additional construction and labour costs cannot be justified.

Question 8. Many of the requirements and design elements for the farrowing and weaner houses are similar. Can the requirements for the weaner pig be met in a combined farrowing–weaner pen so the double stress of movement at weaning is eliminated?

Answer 8. The requirements are similar but not identical. The same total number of pens would be required. However, twice as many farrowing pens would be needed unless the pens were picked up and moved around. The pig self-feeder could not be put on the end because the sow needs access in the rear and the feeder in the front. The flooring is not identical. The ventilation requirements are quite different where the sow is housed. If the pigs are left in the farrowing pens for a few days after weaning and two litters are allowed to mingle during this time, most of the double stress can be eliminated. It does not appear justifiable to combine these two functions.

Pen Partitions

Question 9. Is there any special reason for recommending solid partitions between pens in grower–finisher barns? Will this not affect air-flow and convection currents while increasing building costs?

Answer 9. The solid partition between pens is recommended adjacent to the solid portion of the floor where defecation is to be discouraged. The pigs will tend to defecate where they have nose contact through a grilled partition. Because air enters the edge of the building and flows up toward the ridge, a solid partition parallel to this flow will not obstruct, and may even enhance, the flow by restricting cross-flow. All partitions parallel to the roof ridge must be open. A well-built concrete partition should cost very little more than a good steel partition and will last twice as long.

Flushing Systems

Question 10. Does open-gutter flushing contribute to the transmission of disease from pen to pen or cause any health problems?

Answer 10. No. Open-gutter flushing does not contribute to disease problems. The wastes are highly diluted and rapidly removed from the building at frequent intervals. However, if a disease does break out within a building, it would be best to use fresh water rather than lagoon recycled water for flushing until the problem is under control. Most diseases will move through a slatted floor building just as fast as through an open-gutter building. Because the floors in the open-gutter building stay cleaner, there will be less tracking of manure from pen to pen by the workers.

Although some research has shown that a few indicator organisms can be recycled through an anaerobic lagoon, there is no evidence that any disease has ever been transmitted in this way. Open-gutter flushing in weaner pens does contribute to poorer production and additional disease problems. This is because of the extreme susceptibility of the pigs at this stage in their lives.

Question 11. What about the use of flushing between slats in the tropics?

Answer 11. The development of the equipment and technology for flushing between slats in pig facilities is not sufficiently advanced to recommend it as a production technique in the tropics or in cold climates. Further experimentation and development are needed.

Feeding Systems

Question 12. What are the relative advantages and disadvantages of round versus fence-line feeders in terms of trough space, feed capacity, automatic feeding, and costs?

Answer 12. If one were to recommend one over the other, fence-line feeders would be favoured. They take less space and they replace a partition. In narrow partial-solid-floor pens, the round feeder would encourage defecation in the upper corners of the pen, whereas the fence-line feeder would not. Round feeders are more commonly used in wide buildings with totally slatted floors. Feed wastage is more of a problem with this arrangement. Trough space, feed capacity, and automatic feeding costs would be equal with either type of feeder.

Physiological Conditions

Question 13. It has been stated that temperatures of 35°C are required for piglets and 27–29°C for weaners. Are these figures for temperate climates, or are they also valid in the tropics where the relative humidity is very high?

Answer 13. The temperature requirements of piglets are not affected by relative humidity. For piglets, protection from drafts and contact with cold surfaces is more important than temperature. In farrowing and weaner pens, piglets are very susceptible to disease caused by environmental stress. Therefore, they must have a warm, draft-free environment. During farrowing, a heat lamp is useful. A brooder should then be placed in the farrowing pen for 3 or 4 additional days.

Housing Designs

Question 14. What quantitative gain can be made by using improved pig farm designs?

Answer 14. Basically, there are two benefits from good housing facilities in a tropical climate. The first is an increase in production efficiency as a result of improved environmental conditions and more efficient use of building space. Over time, production efficiency could easily increase by 10%. The second benefit is a saving in labour, as well as an exchange of labour for capital in the form of automation. This could eventually decrease labour inputs by as much as 20%.

Question 15. How are pens kept clean if only 30–50% of the floor is slatted?

Answer 15. Perhaps the best way to answer this question is to summarize the important aspects of pen design for partial slats or open-flushing gutter systems.

- Slope the solid floor toward the gutter.
- Build solid partitions adjacent to the solid floor portion of the pen.
- Build open partitions over gutter or slats.
- Keep pens long and narrow (proportion length to width, 1.2:1 to 2.5:1).
- Floor-feed if possible, always feed toward the top end of the pen.
- Maintain proper pig density (grower, 0.5–0.6 m^2/pig; finisher, 0.8–1.0 m^2/pig).
- Place waterer over slats or gutter.
- Ventilate the solid portion where possible to keep it cool and comfortable.
- Keep the slatted portion light and airy.

Question 16. What should the slope of the floor in the porker pens be to aid drainage?

Answer 16. All porker pens, whether they have open gutters or partial slats, should have the solid portion of the floor slope toward the gutter or slats. This slope should be 7–8% to facilitate good manure movement.

Water Systems

Question 17. Should the height of the nipple waterers in grower and finisher pens be adjustable because the animals are different sizes?

Answer 17. If the waterers are initially installed at an appropriate height for the average size pig that will be housed in that pen, adjustability is not necessary. This assumes that separate grower and finisher pens are provided and that the function of the pen will not be changed.

Landscape

Question 18. Are there benefits, other than the provision of shade from planting trees between buildings?

Answer 18. The area around a tree is cooled not only by shade but also by respiration of the tree. This tends to cool the environment. Trees also help to prevent movement of air-borne bacteria from farm to farm.

Water Cooling

Question 19. Do water sprinklers cool pigs sufficiently to justify their installation?

Answer 19. The cooling effect of added water on the pig is minimal. This evaporative cooling also tends to increase the relative humidity and make it more difficult for the pig to cool itself by respiration. The higher humidity also decreases production efficiency. If open-gutter flushing is used, the pigs can cool themselves in the gutter. In any case, the heat lost from the pig as a result of evaporative cooling in humid climates is not worth any investment in equipment.

Floor Design

Question 20. What is the relative cost of plastic-coated expanded metal flooring compared with concrete slats and galvanized woven wire mesh flooring? What are their relative life expectancies?

Answer 20. In the absence of actual long-term data from the tropics, the table below answers this question as quantitatively as possible.

Material	Relative cost	Expected life (years)
Concrete slats	10	10
Wood slats	5	2
Expanded metal	12	2
Woven wire mesh	13	4
Plastic-coated metal	30	8

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Major component areas in local pig farms and local land allocations and functions.
2. Pen dimensions, calculation of pens needed, and pen management program design for efficient pig production.
3. Farm layout, barn layout, construction trends and practices, dimensions and orientation.
4. Flooring materials, practices, and trends.
5. Design of farms for costing, using local unit costs.

Chapter 5

Environmental Impact of Pig Wastes

This chapter details the physical, chemical, and biochemical properties of wastes as excreted and collected in PFA "wastewatersheds." It also describes an assessment of the environmental impact of pig wastes discharged into estuaries from the wastewatershed of two PFAs. The question and answer portion of the chapter is intended for those uninitiated in the concepts of pollution-measuring parameters. However, it also includes data on metals and other chemical elements plus numerous measurements of the numbers of bacteria and fungi found in pig wastewaters at various stages of treatment.

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Properties of Pig Wastewater

In the design of waste management and pollution control systems and in the assessment of the environmental impact of waste disposal, it is necessary to quantify waste characteristics in engineering terms. Many terms may be used as waste and water quality parameters. Not all of these parameters need to be quantified before devising systems for waste management. However, the design parameters selected must be those that relate to the process being considered and to the water quality standards to be achieved. Environmental impact assessment includes, besides the effects of wastes on water and soil resources, nuisance factors and social and political reactions that cannot always be quantified.

In confined commercial pig production, as practiced in Singapore and in the tropics in general, wastes consist of feces and urine, wasted feed, spilled water from the drinking nipples and leaking pipes, and water used for cleaning the pens and cooling the pigs. Because wastewaters are collected in open drains, they contain runoff water plus soil and other particles carried by the runoff water. The wastewater generated on farms in the tropics is, therefore, not the same as the manure or slurry of farms in temperate and cold climates.

A sampling program was carried out over several years to arrive at design guidelines for the physical, chemical, and biological properties of the pig wastewaters.

Sampling

The results of any test procedure, no matter how well followed, are no better than the sample taken. Therefore, staff were first trained to take representative samples using integrated and composite sampling procedures and equipment. Sampling was carried out for the duration of the flow or, in some instances, continuously for 24 h.

At first, existing government laboratories were used. However, their limited capacity and flexibility could not cope with the 31 different tests run on replicate samples from the 27 sampling points plus additional samples from experimental programs. Purchase of equipment and minor renovations were sufficient to establish a waste analysis laboratory to complement the existing wet chemistry laboratory that was used for feed analysis and animal nutrition at PPRTI. The same laboratory personnel were used after training.

Sampling Network

A network of sampling points was established for the Ponggol PFA (see Fig. 5.1). Additional surveys in the estuaries and beaches at the outlet of the Serangoon River were carried out by government agencies.

Collection of Samples

Samples were collected in 4-L, wide-mouth plastic bottles from the top layer of flow of the rivers. No bottom mud was collected, except in small drains where the entire flow was sampled. Each sample bottle was identified by type and location. The temperature of the sample and the time of collection were clearly marked. All stream-water sample bottles for dissolved oxygen measurements were completely filled to avoid aeration during transport.

Grab Samples

All stream samples in the main body of the rivers were grab samples. They were taken during low tide, from the top 15 cm of the depth of flow.

Composite Samples

Composite samples were taken over periods of 4–8 h. When the construction of a central treatment plant was considered, 24-h composite samples were taken for a week at a time at the proposed site (sampling point 19; see Fig. 5.1).

Sample Storage

All samples were stored in ice boxes on the way to PPRTI, where they were kept at 4°C until analysis. Analysis was initiated within 24 h of collection.

Testing of Samples

The testing procedures for the common parameters used in the characterization of animal wastes and wastewaters were based on *The Standard Methods for the Examination of Water, Wastewater, and Sludges* as revised every 5 years by the American Public Health Association (Washington, DC) and other cooperating scientific societies.

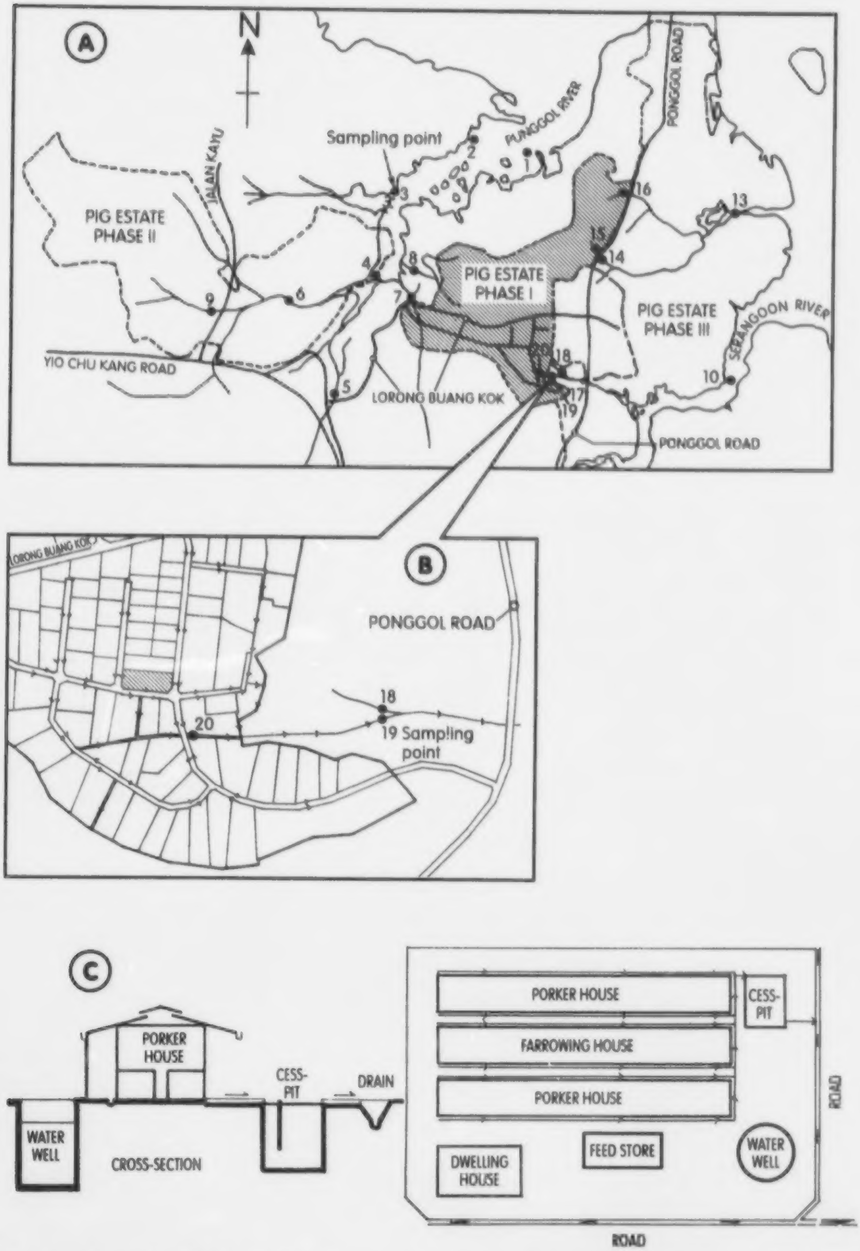
A
N
Sampling point
PUNGGOL RIVER
PONGGOL ROAD
JALAN KAYU
PIG ESTATE PHASE II
PIG ESTATE PHASE I
PIG ESTATE PHASE III
SERANGOON RIVER
YIO CHU KANG ROAD
LORONG BUANG KOK
PONGGOL ROAD
1
2
3
4
5
6
7
8
9
10
13
14
15
16
17
18
19
20
B
LORONG BUANG KOK
PONGGOL ROAD
18
19 Sampling point
20
C
PORKER HOUSE
WATER WELL
CROSS-SECTION
CESS-PIT
DRAIN
PORKER HOUSE
FARROWING HOUSE
PORKER HOUSE
CESS-PIT
DWELLING HOUSE
FEED STORE
WATER WELL
ROAD
ROAD

Fig. 5.1. Location of WWS 19 and typical small farm layout: (A) the Ponggol PFA and its pollution survey network, showing sampling points 1 to 20 (except points 11 and 12 which were further up the Serangoon River); (B) WWS area for sampling point 19; (C) typical farmlot layout.

Waste-Generation Rates

Several approaches were taken to obtain waste-generation rates. They were developed mostly by actual collection of feces and urine in metabolic crates and by monitoring, under controlled conditions, the quantities of waste added to pits below slatted floors and taken from barns with solid concrete floors. The volume of waste was related to the total live weight of the pigs that generated it by weighing the entire pig population during the sampling period.

In one experiment in a building full of porker pigs, the major inputs (feed and water) and outputs (solid and liquid wastes) were measured over several weeks. Solids and water were collected from under the slatted floors in a pit that had been calibrated so that changes in water level were converted to volume of wastewater. The water inputs were measured with water meters.

Water Use

In the aforementioned experiment, water used in the slatted floor barn for drinking and washing was measured for 47 days. During this period, the mean live weight of the porkers was 59.7 kg. The average rate of water use was 17.5 L/porker per day, which was equivalent to 29.3 L/APU, where APU (animal population unit) is 100 kg live weight.

As the pigs grew, daily water usage increased from 13.9 to 23.8 L/porker (27 to 35 L/APU). These figures were combined with those from other pigs to obtain an estimated value for water use for drinking and for cleaning the pens of 20 L/SPP or 36 L/APU. Hourly water withdrawal from the pipeline averaged 0.6 L/APU at night and a little over 2 L/APU during the day. From 0800 to 1700, the porkers consumed 68% of the total water used per day. The water supply was kept under low pressure (less than 3 m) to minimize spillage.

Wastewater Generation

Based on analyses of data over approximately 6 years, design values for both waste and wastewater generation were adapted (Table 5.1). These values were used in the design of all the wastewater-treatment facilities built in Singapore. Table 5.2 compares the Singapore values with major sources of similar data.

Flow Pattern

The wastewater flow pattern of individual farms had a double peak (one in the morning and another in the afternoon) that corresponded to the times at which the pens were hosed down. The flow pattern from an area that served 50 farms (some of which hosed only once) produced a single peak at midday because of overlap and the distance to the sampling point.

The peak flow rate was four times larger than the average flow rate. Generally, the same ratio of four applied to the peak BOD_5 compared with the average BOD_5. The ratio of the peak BOD_5 to the minimum BOD_5 ranged from 7:1 to 12:1. Minimum BOD_5 values were encountered at night (from 1900 to 0700). These extreme variations are critical in the design of

Table 5.1. Properties of pig wastes and wastewaters in Singapore farms.[a]

	Wastes as excreted				Wastewater	
Parameter[b]	kg/day per APU	% TWW	% TTS	% TVS	kg/day per SPP	mg/L
TWW (feces + urine)	8.4	—	—	—	4.54	—
TTS	0.84	10	—	—	0.45	18300
TVS	0.67	8	80	—	0.36	14700
TFS (ash; minerals)	0.17	2	20	26	0.09	3700
TSS	0.69	8.2	82	103	0.37	15000
TDS	0.15	2	18	22	0.08	3300
BOD_5	0.25	3.0	30	37	0.13	5300
COD	0.84	10	100	125	0.45	18300
TKN	0.05	0.6	6	7.5	0.03	1100
TPO (= 2.27 TPP)	0.02	0.25	2.5	3.0	0.01	440
TKO (= 1.21 TKK)	0.01	0.14	1.4	1.8	0.005	220
Hosing/cooling water[c]	37	—	—	—	20	—
TWF[c]	45.4	—	—	—	24.5	—

[a] These values represent the quantities generated and do not account for any losses after excretion. As such, they represent maximum mean design values for preliminary calculations. 1 APU (animal population unit) consists of 100 kg total live weight (TLW). SPP (standing pig population) averaged 54 kg for all pigs (sows, piglets, boars, weaners, and porkers). The term mg/L is the concentration of waste expected under the traditional use of water to hose down the pig pens at a daily rate of 20 L/SPP. The total wastewater flow (TWF) = 20 + 4.54 = 24.54 L/SPP per day. Concentrations change in proportion to the volume of water used to remove the wastes each day. In flushing systems, the daily volume of water used should be about 30 L/SPP, making TWF = 30 + 4.54 = 34.54 L/SPP per day.

[b] See list of Acronyms and Abbreviations for definitions.

[c] Units: L/day per APU or per SPP.

treatment processes that are sensitive to changes in the characteristics of the effluent.

Cesspit Effects

The farms in Phases I and II of the Ponggol PFA were required by the government to install a cesspit, which was an underground concrete tank with a capacity of about 130 L/SPP. Some of the farms partitioned the tank into two or three interconnected compartments to prevent short-circuiting of flow and to increase the residence time for solids. The cesspits were to be desludged periodically. They were to be a short-term solution until proper waste-treatment facilities were installed. The use of a cesspit was a standard practice imposed by most governments in the tropics.

Seven cesspits, ranging in size from 90 to 270 L/SSP, were investigated to determine their effectiveness in changing wastewater characteristics. Typical results for analyses of data for the first 8 weeks of sampling are given in Table 5.3.

Comparing cesspits using only concentration levels is not inappropriate

Table 5.2. Comparison of Singapore waste and wastewater parameters with other sources.

Parameter[a]	Singapore (mean)	Malaysia[b]		ASAE 1983 (mean)	Taiganides 1977 (mean)
		Mean	80%		
TWF	20	30	—	—	—
TTS	840	90	810	550	690
TVS	670	540	630	440	570
TSS	690	560	660	—	—
COD	840	660	790	510	710
BOD_5	250	270	320	180	220
TKN	50	32	41	41	39

[a] See list of Acronyms and Abbreviations for definitions. Units: TWF, L/SPP per day; all others, g/APU per day.

[b] Source: Teoh et al. (1988). The 80% level was equalled or exceeded 20% of the time.

because the amount of wash water used at the time of the samplings varied from farm to farm. Therefore, the percentage of influent leaving in the effluent was tabulated for each cesspit. The percentage of influent in the effluent for chemical oxygen demand (COD) ranged from 18 to 98%; for TTS, 25 to 137%; for TVS, 16 to 128%. Sometimes the concentration of a parameter in the effluent was greater than in the influent because of turbulence in the cesspit. The ratio TVS/TTS, which indicates the state of solids mineralization, ranged from 0.44 to 0.75.

Using data on raw waste and the results from sampling point 20 (to which all the cesspits under observation drained), it was calculated that cesspits could reduce, from raw pig waste values, COD by 45%, TTS by 42%, and TVS by 33% (see Table 5.1). TTS in the sludge of the cesspits ranged from 3 800 to 164 000 mg/L with an average of 64 000 mg/L. The average ratio of TVS/TTS for sludge was 0.54 (0.20–0.77); for the mat of floating aerosols and solids, which invariably formed in the cesspit, the ratio was 0.73 (0.64–0.83). This indicates that the floating solids in the mat were not mineralized to the same degree as the solids in the bottom of the cesspit.

The large commercial farms in Phase I PFA were required to have pits under the slatted floors. These pits provided a longer storage period than the cesspits in the small farms. However, the effect on waste properties was about the same. BOD_5 was reduced by more than 50% in the pit, and TVS was reduced by 32 to 58%. The characteristics of the wastes in the pits under the slatted floors are given in Table 5.4.

Effect of Sedimentation

At the experimental pig production facilities at PPRTI, sampling was carried out almost daily on the wastes that were used in the various treatment experiments. Wastewater from the holding tanks was pumped daily through four parallel fiberglass sedimentation tanks. The characteristics of the wastewaters and the supernatant after settling are summarized in Table 5.5. The daily BOD generation rate was estimated as 0.13 kg

Table 5.3. Cesspit performance sampling data.

	COD (mg/L)			TTS (mg/L)			TVS (mg/L)			Eff.		Inf.	Cesspit compartments		
Farm	Inf.	Eff.	%[a]	Inf.	Eff.	%[a]	Inf.	Eff.	%[a]	TVS/ TTS	Ash[b] (mg/L)	Ash[b] (mg/L)	No.[c]	m^3/SPP[d]	Age[e] (months)
F22	23398	8096	35	19810	8200	41	16832	4906	29	0.60	3298	2978	3	0.27	12
F45	21691	12552	58	17647	11306	64	13224	5539	42	0.49	5767	4423	1	0.13	0
F46	33675	24829	74	26215	23518	89	19837	17629	89	0.75	5889	6378	5B	0.12	0
F64	13171	2305	18	11341	3984	35	8118	1753	22	0.44	2231	3223	5A	0.20	16
F95[f]	23607	23126	98	13346	18963	139	10300	13227	128	0.70	5736	3546	1	0.09	3
F75	30653	13864	45	20710	10117	49	15489	6600	43	0.65	3517	5221	1	0.18	6
F10[g]	30738	4558	15	21784	5382	25	18453	2982	16	0.55	2400	3331	5B	0.21	1
Avg.	25497	12029	47	19100	11638	63	14888	7085	48	0.61	4553	4212			
Avg.[h]	36438	14438	39	24957	12844	51	19181	8821	46	0.69	4023	5776			

Note: Inf., influent; Eff., effluent; see list of Acronyms and Abbreviations for other definitions.

[a] Percentage of influent leaving the cesspit through the effluent.

[b] Ash = TTS − TVS = TFS.

[c] Baffle type between compartments: A, extends above liquid; B, top is below liquid level.

[d] Computed using raw waste data and results of sampling point 19.

[e] Age at the beginning of the test period.

[f] Farm 95 was added during the 9th week of the test period.

[g] Farm 10 had an Imhoff Tank.

[h] From 12 June to 8 August.

Table 5.4. Characteristics of wastewaters from pits under slatted floors.

	Hold and discharge[a] (sluice gates)[b]	Overflow[a] (weir)[b]
Volume of wastewater (L/APU per day)	46.7	47.0
BOD (kg/APU per day)	0.08	0.10
TVS (kg/APU per day)	0.23	0.37

[a] System to manage excess.
[b] Flow discharge.

Table 5.5. Characteristics of wastewater at PPRTI.

Parameter[a]	Fresh (mg/L)	Supernatant (mg/L)	Reduction %
TTS	5633 ± 205	2809 ± 94	50
TSS	4245 ± 156	733 ± 68	83
BOD_5	2665 ± 128	1514 ± 88	43
COD	6255 ± 272	2049 ± 108	67
TKN	—	256 ± 12	—
TAN	—	168 ± 8	—

Note: Values represent the average (± standard error) of over 200 observations.
[a] See list of Acronyms and Abbreviations for definitions.

BOD/APU. This value is similar to that calculated from the monitoring of wastewater discharge from commercial farms in the Ponggol PFA.

PFA Wastewatershed Characteristics

Pig farming areas as they were planned in Singapore in the early 1970s and as they emerged in Malaysia and other countries were clusters of farms along small creeks in small watersheds that would become "wastewatersheds" (WWSs). The two main advantages of these sites when treated as WWSs were the capability of the natural canal to carry away the farm wastewaters and the access to upstream runoff water. In such sites, PFAs become WWSs that can adopt central treatment plants. The main advantage of centralized treatment is economy of scale. Farmers also like the idea because they need not get involved in the operation of processes with which they have no practical experience. A major disadvantage is that the treated effluent cannot be recycled on the farms because it would spread diseases. Reuse of treated water for waste flushing is recommended only on closed-herd farms.

One PFA lent itself to a comparison of centralized and on-farm treatment. The Ponggol PFA and its pollution survey network, the WWS area for sampling point 19, and a typical farmlot layout are shown in Fig. 5.1. Extensive sampling was carried out at sampling point 20 because of the physical shape of the drain at that point; the data were extrapolated to point 19, which had a larger WWS area and was in a low region where a treatment plant could be built. The data collected were used to design, in sufficient detail, 19 treatment combinations and to determine the cost of each. The approaches taken and some of the data collected are highlighted because of their relevance to similar situations elsewhere.

Wastewatershed 19

There were 86 farm lots draining into the WWS at sampling point 19 (WWS 19), but only 76 lots were actually occupied. Each lot was a full closed-herd farm that operated independently from its neighbours and was enclosed by a fence. Each farm had a cesspit. Effluent from the cesspits flowed by gravity in concrete drains through sampling point 20, past point 19, and into the mangrove area of the Serangoon River. The logical place to build a pilot treatment plant was at sampling point 19.

An engineering survey of the WWS included the tracing of drains, detailed topographical mapping, determining animal population, recording type of production, calculating the roofed area, and measuring drainage area. The total drainage area was 62 ha, of which 19 ha contained roofed barns and buildings. Roofed area and water storage area amounted to 31% of the total land area of the watershed. Assuming 100% collection of precipitation and no losses, rains would yield 484 500 m^3 of water annually, estimated to represent 75% of annual demand. The rest of the water had to be supplied.

Pig Population

Until the outbreak of Aujesky's disease in March 1978, actual SPP was in agreement with projected SPP. During March and April 1978, SPP was declining at a rate of 250 SPP/day, mainly from the death of piglets. Consequently, the average live weight per SPP increased during that period; the live weight per pig returned to the normal average of 54 kg once the disease was brought under control.

Wastewatershed Sampling

Weekly sampling was initiated in May 1976 and carried on until May 1978. During this period, in situ measurements and sample collections were made three times a day between 1000 and 1500. Three grab samples of equal volume were collected and composited.

Three series of 24-h continuous samplings were carried out for periods of 5, 4, and 3 days in January, September, and October 1977. In January, the flow was determined by measuring the depth of water and silt in the drain and the velocity of the flow. Grab samples were collected every 30 min and composited. In September and October 1977, however, an automatic sampler was used in conjunction with a 60° V-notch weir. Samples were taken automatically in proportion to the flow, which was automatically and continuously monitored. Because the data collected using the automatic sampler were more accurate than those collected in January 1977, they were used in developing design parameters.

Wastewatershed Design Data

Wastes defecated by the pigs, washwater, base flow from the watershed, and surface runoff water were assumed to constitute the total wastewater flow of WWS 20. The flows at night from 2100 to 0500 were assumed to constitute the base flow. It was also assumed that the base flow was proportional to the watershed area and that it would continue at the same rate during daylight hours. Fortunately, it did not rain during the three 24-h sampling periods, so the wastewater flow could be calculated by subtracting the base flow from the measured flow. The daily volume of wastewater generated from the pig pens was calculated as 36 L/APU or 19.4 L/SPP.

The observed, calculated, and designed values of the daily quantities of the major pollutants at WWS 20 are given in Table 5.6. Almost 58% of the BOD_5, 63% of the COD, and 61% of the TTS theoretically defecated by the pigs were either retained in the cesspits or lost, and thus were not found at the sampling point. These reductions and the age of the wastewater need to be considered in the selection of treatment processes.

Flow Pattern

The peak flow of wastewater and pollutants occurred around noon. The peak runoff rate for a 23-min storm (equal to the time of concentration of WWS 19) and 10-year recurrence interval was almost 100 times larger than the peak wastewater flow of 5 m^3/min. It is not economical to design a pumping station and a treatment plant catering to such variations in flow. This is the main disadvantage of centralized systems for a WWS.

By not treating rainfall runoff that exceeded a rate of 5 m^3/min, 16.5%

Table 5.6. Observed mean values at WWS 20 and adopted design values.[a]

	Observed mean values				Adapted WWS design value
	Weekly (Apr. 1977 to Oct. 1977)	Daily (24-h)		Overall mean	
Pollutant parameter[b]		Sept. 1977	Oct. 1977		
Dry weather flow (base flow + TWF)	—	—	—	46	46
BOD_5	0.102	0.101	0.114	0.106	0.10
COD	0.260	0.357	0.328	0.315	0.32
TTS	0.328	0.331	0.330	0.330	0.33
TVS	0.190	0.209	0.205	0.201	0.20
TSS	0.219	—	—	—	0.22
SLS	3.02	—	—	—	—
TKN	—	—	—	0.039	0.04
TAN	—	—	—	0.029	0.03

[a] The adopted design values are for the WWS waste flow that goes through the cesspits first; as such, they are lower than the quantities of raw wastes generated on the pig farms. It should be noted that the daily base flow was 10 L/APU; thus, the total wastewater flow (TWF) would be 46–10 = 36 L/APU per day.

[b] Units: dry weather flow, L/APU per day; SLS, mL/L; all others, kg/APU per day. See list of Acronyms and Abbreviations for definitions.

of the pollutants would bypass the plant. In other words, 83.5% of the pollutants going through point 19 would be treated during storm runoff periods. Because of the dilution, the water quality of the bypassed wastewater would be acceptable. It was recommended that the open drain be designed with a weir bypass for flows above the peak wastewater flow during periods of no rain.

Environmental Impact of the Ponggol PFA

In 1980, relocation and intensification of the farms at the Ponggol PFA had progressed to the stage that an assessment of the environmental impact seemed appropriate and possible. Water samples had been collected from the Ponggol and Serangoon rivers since the early stages of pig farm relocation. Hence, a useful data base existed. The existence of some accumulated data, however, could not be assumed to make the assessment simple, either to perform or to interpret. The discharge and flow of farm wastes in the mangroves of the rivers was a complex process occurring within a dynamic hydrologic system that had extensive variability and numerous simultaneous interactions.

A previous study of water quality in this area was conducted by a government agency from October 1978 to March 1979. That study involved a brief water-quality sampling program, a series of flow measurements to evaluate dilution factors between each estuary and the harbour, and an effort to identify the sources of the pollutants detected. The data collected as part of that study were considered in this assessment.

Pig wastes were not the only potential pollutants entering the Ponggol and Serangoon rivers. Each also received domestic sewage. The Serangoon River also received effluent discharges from the Kim Chuan Sewage Treatment Plant (see point 10, Fig. 5.1)

Water Quality

Effect of Tide

Any natural water body will vary in constituent concentrations in response to differences in quality of inflow because of rainfall and runoff. Estuarine streams, such as the Ponggol and Serangoon rivers, have tide as an additional source of variability. Tides produce a predictable rise and fall of water level that creates a reciprocating movement of water in the lower reaches of the river four times a day. Tides trap pollutants and mix fresh water with sea water. During high tide, pollutant concentrations decrease as a result of dilution with water from the area outside the river. During falling tide, the stream, which flows at an accelerated pace because of the decreased water level at the lower end, brings undiluted wastewater from upstream into the estuarine area.

Wastewaters

The quantity of waste depended on weather conditions and on actions on the farm itself. There was an additional element of variability after the wastewater left the pig farm and before it became part of the lower river system. Pig farm waste spent a variable length of time in the mangrove areas and in upper basin pools subject to tidal actions. Within these areas, solids settled, chemical transformations occurred, and biological degradation proceeded. The quality of water leaving these areas was markedly different from the wastewater that entered. The extent of this transformation was difficult to predict in a quantitative manner because it varied with rainfall pattern, total waste flow, and the interaction of these variables with the tidal action of the river.

Data Analysis

The only approach to interpreting data was to use statistical means and standard deviations to state, with moderate confidence, that measurements from one source represented a different situation than those from another. Figure 5.2 presents the data for sampling point 13 in the Ponggol PFA, which was the outlet point for WWS 15 and WWS 16. In general, BOD_5 remained below 50 mg/L despite drastic increases in the pig population. The BOD_5 at the edge of the estuary represented only 10% of the average BOD conveyed through the earth drains from the farms (measured at 2 430 mg/L) and less than 5% of the wastewater generated in the pig pens (see Table 5.1).

A summary of the data collected for the Ponggol River mouth is given in Table 5.7. BOD_5, Kjeldahl nitrogen (TKN), and total ammonia nitrogen (TAN) were selected for study because farm wastes would cause an increase in all three of these parameters if they reached the sampling points in significant quantities. The data show the variability that was expected. Some of the samples taken at what may be considered the mouth of the river (point 1, Fig. 5.1) show no trace of pollution. The data did not suggest any change in the parameters during the 1975 through 1979 period of sampling. Table 5.7 also shows that there is no detectable difference in water quality among the three sampling points in the mouth of Ponggol River. This supports another independent study of the Ponggol and Serangoon rivers in 1979, which concluded that the two rivers were confined basins of uniform pollutant concentrations.

The Serangoon River, which received discharge from farms in Phase I of the Ponggol PFA, was sampled at several locations. The data from those samplings (Table 5.8) show that there were neither statistically discernable changes in BOD_5, TAN, and TKN from 1974 to 1979 nor a detectable difference between the two sampling points (10 and 11), one of which was downstream of the pig wastewater flow and the other upstream.

Other surveys also indicated that the water quality did not change with the stage of tide. Both on-site observations and logic would suggest that there would be a difference. Nevertheless, the survey data indicated that other sources of variability, such as the outfall of the sewage treatment

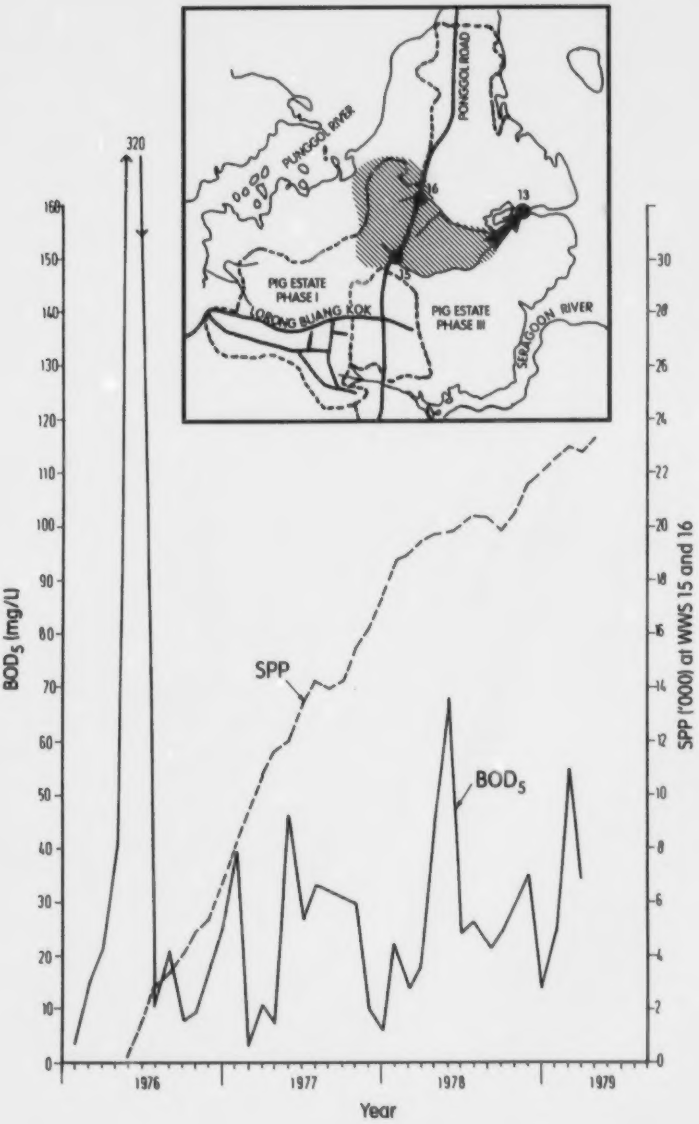

Fig. 5.2. Changes in estuary water quality (sampling point 13) with increases in SPP. BOD_5 changed from an average of less than 10 mg/L before the formation of the PFA in 1976 to 20–50 mg/L when the SPP had reached 24 000. The reason for the 320 mg/L BOD_5 at the beginning of the sampling program is not known; it could be due to sampling error. The samples were grab, not composite.

Table 5.7. Historical record of water samples of Ponggol River, 1974–1979.[a]

Year[b]	BOD_5 (mg/L)	TKN (mg/L)	TAN (mg/L)
		Sampling point 1[c]	
1979 (13)	7.8 ± 8.4 (2–34)	6.2 ± 2.7 (2.2–10.2)	4.4 ± 2.5 (0.1–8.7)
1978 (10)	3.8 ± 3.0 (0–8)	6.6 ± 3.7 (1.3–9.5)	3.4 ± 1.6 (1.6–6)
1977 (13)	6.2 ± 5.0 (1–20)	6.5 ± 2.3 (3.0–17.8)	3.1 ± 1.0 (1.6–4.4)
1976 (21)	5.2 ± 3.2 (0–12.1)	—	1.5 ± 1.0 (0.2–4.6)
1975 (14)	8.4 ± 3.1 (3.3–13.9)	—	1.4 ± 1.7 (0.2–5.8)
		Sampling point 2[c]	
1979 (13)	8.2 ± 4.4 (4–19)	8.2 ± 3.6 (2.7–15)	6.2 ± 2.7 (1.4–10.8)
1978 (10)	5.9 ± 3.5 (1–13)	7.9 ± 3.6 (1.7–14.3)	4.7 ± 2.9 (2.9–10.2)
1977 (13)	8.0 ± 6.4 (0–19)	6.7 ± 2.6 (5.1–14.0)	4.0 ± 1.9 (2.0–8.8)
1976 (11)	7.8 ± 9.4 (0.2–35)	—	1.9 ± 1.1 (0.5–4.6)
1975 (7)	7.2 ± 1.8 (4.5–9.9)	—	1.6 ± 1.5 (0.2–4.2)
1974 (10)	12.1 ± 4.4 (5.7–16.3)	—	2.5 ± 1.2 (1.2–5.2)
		Sampling point 3[c]	
1979 (13)	9.9 ± 3.8 (5–19)	11.1 ± 4.5 (4.0–20.4)	8.1 ± 4.0 (2.2–10.8)
1978 (10)	12.7 ± 13.1 (3–46)	11.0 ± 6.3 (3.0–22.6)	8.1 ± 5.4 (4.0–18.7)
1977 (13)	10.5 ± 4.2 (2–15)	7.5 ± 1.8 (4.7–11.0)	4.2 ± 1.8 (0.2–6.9)
1976 (11)	8.9 ± 6.2 (1.9–22)	—	2.8 ± 1.0 (1.0–4.2)
1975 (7)	16.3 ± 19.3 (7.3–56)	—	3.0 ± 2.8 (0.4–9.0)
1974 (10)	17.2 ± 8.7 (8.7–38)	—	3.3 ± 1.4 (1.6–5.2)

[a] Values are means ± standard deviation, with range in parentheses.
[b] Number of samples is shown in parentheses.
[c] See location of sampling points in Fig. 5.1.

plant and, of course, the filtering capacity of the tropical mangroves had a more important influence on water quality parameters.

Conclusions and Discussion

Monitoring of the Ponggol and Serangoon rivers started before PFA development within their drainage basins. Coincidental with this development was an increased awareness of environmental quality and social issues. The press reported complaints from Muslim fishermen from Malaysia that pollution from the pig farms had affected fishing in the waters between the two countries. Although surveys in those areas showed no evidence of changes in water quality, the political implications were such that environment ministers and their senior technical staff from both Malaysia and Singapore visited the PFA sites.

Based on the technical analyses of the samples taken from 1977 to 1981, the environmental impact of the pig wastewaters from the Ponggol PFA

Table 5.8. Historical record of water samples of Serangoon River, 1974–1980.[a]

Year[b]	BOD$_5$ (mg/L)	TKN (mg/L)	TAN (mg/L)
Sampling point 10[c]			
1980 (8)	14.0 ± 6.1 (9–22)	10.3 ± 4.5 (6–20)	6.0 ± 5.6 (5–13)
1979 (12)	17.7 ± 11.5 (5–38)	11.9 ± 3.5 (8–16)	8.7 ± 2.1 (5–11)
1978 (10)	25.9 ± 16.2 (9–64)	19.6 ± 7.4 (10–36)	13.3 ± 4.9 (6–21)
1977 (12)	19.1 ± 7.1 (8–30)	14.0 ± 2.5 (11–21)	9.6 ± 2.4 (6–15)
1976 (12)	11.1 ± 4.5 (5–21)	—	8.0 ± 2.0 (5–12)
1975 (7)	12.4 ± 10 (5–32)	—	7.2 ± 5.9 (2–20)
1974 (27)	14.6 ± 14.6 (7–23)	—	
Sampling point 11[c]			
1980 (8)	8.9 ± 4.9 (4–16)	9.4 ± 2.4 (6–13)	8.0 ± 2.1 (5–11)
1979 (12)	9.6 ± 5.8 (1–21)	11.6 ± 4.9 (6–19)	8.3 ± 3.8 (1.3–14)
1978 (10)	14.7 ± 9.2 (7–38)	15.1 ± 6.0 (8–18)	10.8 ± 3.3 (3.5–14)
1977 (12)	15.3 ± 10.2 (1–39)	12.7 ± 1.9 (10–16)	9.2 ± 2.4 (6–13)
1976 (12)	13.4 ± 8.2 (3–25)	—	9.3 ± 2.7 (3–14)
1975 (7)	12.5 ± 6.6 (9–24)	—	7.1 ± 2.5 (2–10)
1974 (12)	21.2 ± 7.4 (7–33)	—	—

[a] Values are means ± standard deviation, with range in parentheses.

[b] Number of samples is shown in parentheses.

[c] See location of sampling points in Fig. 5.1.

may be summarized as follows:

- Pig farm wastes were entering the drains and natural tributaries of both the Ponggol and Serangoon rivers but were not having a measurable impact on water quality at the lower ends of these two estuarine streams. Water quality data from 1974 through 1979 showed no statistically significant change. Yet, during this same period, the number of pigs within the drainage basins increased eightfold.

- There were several waste sources entering the Ponggol and Serangoon rivers, including a sewage-treatment plant and sludge-drying beds. These wastes, which entered the river without first passing through extensive mangrove areas, were more likely reflected in the river quality analyses than were the pig farm wastes.

- The mangroves and other shallow water areas were providing significant natural treatment of pig farm wastes. As a result, these areas were accumulating heavy deposits of organic sludge, were the sites of active anaerobic decomposition, and were a growing source of objectionable odours.

- Nothing in the data indicated that pig farming was having, or likely would have, an adverse impact on water at public beaches several miles from the mouths of the rivers.

- Pig farm wastes were found to be amenable to physical and biological waste treatment processes that simulated the natural processes taking place in the mangrove areas, i.e., anaerobic lagoons would provide the most practical treatment area.

Questions and Answers

Question 1. What are the differences between the terms wastewater, manure, slurry, sludge, and shud?

Answer 1. Pig waste consists of faeces and urine plus wasted feed and water spilled from the drinking nipples. However, in barns where more than 10 L of water is used per pig per day to clean the pens and cool the pigs, as is done in the tropics, excreta and feed wastes become *wastewater*, which flow readily unless stored. Total solids (TTS) content of wastewater is normally less than 3%. Pig waste that contains 3–7% TTS is differentiated from wastewater and is called *sludge*. If the amount of water used daily is less than 10 L/SPP, as is the case in temperate climates where the waste is stored under slotted floors before it is pumped, the mixture is normally referred to as *slurry*. In cold climates where straw and sawdust are used to absorb the urine, the mixture is termed *manure*, and it can be handled mechanically with solids handling equipment. When animal excreta are mixed with mud in an outdoor feedlot, the mixture is termed *shud*.

Question 2. What is the importance of a representative sample?

Answer 2. The results of any test procedure are no better than the sample taken. A representative sample is extremely difficult to obtain and must be taken with care by experienced personnel. Sampling devices for liquid wastewaters have been developed, and attempts are being made to standardize them (to obtain the most current information, consult local environmental health or agricultural agencies, or United Nations publications).

Care must be taken in handling samples to ensure they do not deteriorate before they are tested in the laboratory. Representative samples can only be obtained with integrated or composite sampling over a period of time, over several sampling points, or both. Animal wastes and wastewaters, because they are basically organic in nature, undergo changes through biofermentation that takes place because of the large number of microorganisms present. If samples are not tested within a few hours, they should be stored at 4°C. Preservation of samples with chemicals or organic preservatives is not recommended if they are to be tested for more than one parameter. If storage is necessary, then preservatives that retard biological action are preferred. Storage at 4°C is as good a preservative procedure as the addition of any chemicals.

Question 3. What are the differences between grab, composite, and integrated samples?

Answer 3. Grab samples are acceptable for large feedlots or for pig farming areas whose pig population and feeding procedures remain the same over a long period of time. The same is true for well-established lagoons or even for monitoring large treatment plants with uniform flow rates.

Whenever possible, it is preferable to collect composite samples, which are generally a mixture of grab samples collected at the same sampling point over a period of time (the standard period is 24 h). Composite samples must be collected in proportion to the waste or wastewater stream quantities, which change with time. This is important, particularly in pig farms where the pens are hosed with water twice a day and all the wastes leave the barns at this time. Many automatic sampling devices are available for grab, composite, or integrated sampling.

Integrated samples are mixtures of samples collected simultaneously from different points. Integrated sampling may be appropriate for evaluating the impact of wastewater discharge in a river or lake or for determining the treatability of wastewaters from agro-complexes combining animal production and processing.

Question 4. What parameters are used to characterize the solids in pig wastes?

Answer 4. Total solids (TTS) is the residue remaining in a dish after evaporation at 103°C. TTS is the sum of the total suspended solids (TSS, or filterable residue) and total dissolved solids (TDS, or nonfilterable portion). Total solids also include all inorganic solids (TFS) and all organic matter (TVS), except the portion that is volatile below 103°C. Ash or fixed residue is the residue remaining after ignition at 550°C. Volatile matter is the solids volatilized after igniting the sample at 550°C. This matter is calculated by subtracting the fixed residue from the total residue. Strictly speaking, the loss in weight on ignition of solid wastes is not all due to organic matter. It may include losses as a result of volatilization of mineral salts. Tests on total organic carbon, or chemical oxygen demand (COD), are better approximations of organic matter content.

Except in drinking water standards, tolerance levels for TTS are rarely established. Standards are usually set for TDS (preferably below 500 mg/L, but not above 5 000 mg/L), particularly if the wastewater is to be reused.

TSS is a parameter used as a water quality standard in streams and treatment plant effluents. Nonfilterable residue includes floating solids, which can create a nuisance, and settleable solids, which when discharged into a stream may settle to the bottom and contribute to the development of nuisance bottom sediments. Settleable solids are reported, normally, in millilitres per litre; total solids and fixed solids in milligrams per litre; and solid wastes in grams per litre. Volatile and fixed residue determinations are also made on nonfilterable and filterable solids. These tests are used in both the design and monitoring of wastewater treatment plants.

The size of the particles determines their classification in water. Particles larger than 0.3 µm are considered to be in suspension and are measured with a glass fibre filter disk placed on a membrane apparatus or at the bottom of a suitable Gooch crucible. Particles with diameters below 0.3 µm are dissolved solids. Dissolved solids include colloidal particles with diameters between 0.003 and 0.3 µm. Particle sizes and shapes are critically important in the design and evaluation of solids separation devices, such as screens, decanters, and sedimentation devices, and in pumping.

Question 5. What is the significance of metals and other inorganics in the waste and wastewater stream?

Answer 5. The presence of metals, particularly heavy metals, in wastes and wastewaters is a matter of grave concern because they may accumulate to concentrations that can disrupt biological treatment processes and create toxicity problems.

Copper is included in pig feed for medical reasons. Most of it is excreted with the feces. The suggested maximum copper content in drinking water is 0.5 mg/L. Standards for other metals in water are given in Chapter 2. Data on metals and other inorganics in raw pig wastes and after sedimentation are given in Table 5.9.

Question 6. How is oxygen involved in water pollution?

Answer 6. Dissolved oxygen (DO) is an important water quality parameter. Normally, water quality standards for streams specify minimum levels of DO to be maintained in the river depending on the use being made of the water and the prevailing temperatures. Dissolved oxygen is directly related to temperature and to chloride concentration in the water. Most chemistry handbooks have tables of the solubility of oxygen in water. For example, at 4°C and zero chloride concentration, saturation DO is 13.1 mg/L, but it is only 7.6 mg/L at 30°C.

There are two methods of measuring DO. One is iodometric, of which the most commonly used technique is the "Winkler" method. The second is the membrane method. Instruments with membrane electrodes capable of measuring instantly, or of monitoring, DO are available and should be used in wastewaters in which organic compounds may interfere with DO measurements made by iodometric methods.

Table 5.9. Heavy metals and physicochemical characteristics in raw wastes and after sedimentation.[a]

	Raw waste in sump tank (mg/L)	Primary sedimentation tank		
		Influent (mg/L)	Primary sludge (mg/L)	Overflow effluent (mg/L)
Mercury	0.009 (ND–0.07)	0.0005 (ND–0.003)	0.0006 (ND–0.003)	0.0008 (ND–0.004)
Arsenic	0.032 (0.015–0.06)	0.028 (0.018–0.05)	0.064 (0.03–0.10)	0.013 (0.01–0.02)
Copper	1.79 (0.6–3.90)	1.69 (1.00–2.90)	5.16 (3.40–8.20)	0.90 (0.34–2.20)
Zinc	4.89 (1.8–14.80)	3.40 (1.80–6.20)	10.61 (2.80–19.00)	1.89 (0.99–4.50)
Lead	0.19 (0.07–0.33)	0.14 (0.07–0.23)	0.29 (0.08–0.45)	0.10 (0.01–0.38)
Cadmium	0.04 (0.02–0.08)	0.025 (ND–0.03)	0.05 (0.03–0.10)	0.015 (ND–0.03)
Chromium	0.74 (0.20–1.45)	0.62 (0.15–1.20)	1.34 (0.55–2.00)	0.47 (0.12–0.88)
pH	6.97 (6.67–7.28)	7.09 (6.83–7.41)	7.59 (7.25–7.85)	7.20 (7.00–7.42)
COD	6050 (466–18689)	4298 (3496–7136)	10342 (3710–16933)	2366 (991–5501)
TTS	6463 (2850–14600)	4525 (3200–6350)	11605 (6200–17200)	2879 (2200–5600)
TSS	3947 (1300–11667)	2683 (1600–4667)	8709 (3800–14000)	1428 (667–4333)
TVS	4617 (2000–11300)	3050 (1950–4450)	7464 (3500–11550)	1724 (1100–3550)
TKN	387 (137–809)	372 (220–508)	564 (247–878)	358 (288–453)
TAN	246 (50–350)	288 (210–390)	308 (230–380)	311 (280–380)
Phosphorus	154 (98–380)	153 (100–250)	297 (174–504)	127 (88–206)

[a] Values are averages followed by the range in parentheses. For the heavy metals, 8 samples were taken; for the physicochemical parameters, 12 samples. ND, not detected. See list of Acronyms and Abbreviations for other definitions.

Wastes and wastewaters discharged into a stream exert an oxygen demand that is satisfied by the DO of the water. To maintain a normal balance of biological forms in a river or lake, a certain amount of organic matter and nutrients must be present. As long as the waste load on a stream is below the assimilative capacity of the stream, the normal biological flora and fauna will be predominantly aerobic. A waste load exceeding the stream's assimilative capacity will cause excessive growth of bacteria that, in turn, may consume all of the DO, and cause anaerobic conditions to develop.

Fish and other aquatic life are greatly dependent on dissolved oxygen. Lack of oxygen stresses fish, particularly game fish. Trout are very sensitive to oxygen levels and require a minimum of 5 mg/L DO, whereas carp, a scavenger fish, can survive in water containing as little as 1 mg/L DO. Typical water quality standards designed to maintain good aquatic life for cold-water fish populations establish DO levels of 6 mg/L as a minimum. For warm-water fish populations, the DO standard is normally set at 5 mg/L, and must never go below 4 mg/L. It is generally conceded that the critical level for fish survival is 3 mg/L DO. Stream waters intended for industrial cooling and processing are required to maintain the DO above 1 mg/L at all times, with an average of 2 mg/L. These examples are given to aid understanding of the relevance of waste parameters to environmental health management. For specific rivers or situations, local or national standards must be consulted.

The level of DO in a stream containing dilute wastewater is dependent on physical, chemical, and biological activities, but the rate at which oxygen is depleted depends mainly on the microbial activity in the water. Re-aeration of swiftly flowing shallow streams can occur rapidly because the high turbulence and mixing that occurs exposes more water surface to the air. Deep, slow-moving, warm-water rivers in the tropics have difficulty recovering from waste overload. Oxygen solubility decreases as temperature increases, while bacterial activity increases, thus, the assimilative capacity of a stream for oxygen-demanding wastes is lower during warm than cold periods of the year. That is why stream water-quality standards specify temperature levels and rates of change of temperature over a period of time.

Question 7. What are the various forms of nitrogen and their role in waste management?

Answer 7. The forms of nitrogen that have environmental health significance are ammonia, nitrate, nitrite, and organic nitrogen. Total nitrogen, or "Kjeldahl nitrogen" (TKN), is the sum of ammonia and organic nitrogen. For solid samples from pig farms, the preferred technique is to determine Kjeldahl and ammonia nitrogen separately on each sample and calculate organic nitrogen by subtraction.

All of these nitrogen components are interconvertible forms in the nitrogen cycle. Nitrogenous compounds in pig wastes are mainly in organic forms that are decomposed by heterotrophic bacteria to produce ammonia. In dilute wastewaters, under high temperatures and high pH, ammonium nitrogen is oxidized to nitrite (NO_2^-) and subsequently to nitrate (NO_3^-) by bacterial action.

Oxidized forms of nitrogen are water soluble and may be lost in water systems, leached out of soil systems, or used by plants to produce organic compounds such as plant proteins. These proteins are eaten by animals and humans and their wastes produce organic forms of nitrogen that re-enter the nitrogen cycle. However, nitrates may also be reduced under anaerobic conditions through denitrification. Denitrifying bacteria, in the presence of organic carbon sources, reduce nitrates to nitrites and, eventually, to nitrogen gas (N_2). Nitrogen is lost as gas in the denitrification process. Nitrification–denitrification processes can, therefore, be manipulated in a wastewater treatment system to reduce or conserve nitrogen content, or to determine the form of nitrogen to be released in the environment.

Nitrogen content is important in pollution control because of its involvement in eutrophication; its demand for dissolved oxygen; the potential health hazard of high concentrations of nitrates and nitrites in drinking water, particularly for young piglets; and the toxicity of high concentrations of ammonia nitrogen to fish and to biological systems. Nitrogen is also important in anaerobic digestion because methane-forming bacteria are extremely sensitive to the presence of various chemicals in their environment, including excess ammonia. Ammonia is produced by the diminution of organic nitrogen, the hydrolysis of urea, and the reduction of nitrate under anaerobic conditions. Organic nitrogen in animal wastes includes compounds such as proteins, peptides, nucleic acids, and urea, all of which are always present in the pig waste stream.

The sum of nitrate and nitrite nitrogen represents total oxidized nitrogen. Oxidized nitrogen in water supplies can be hazardous to young piglets because of its effect on the transfusion of oxygen in the blood stream.

The standards for drinking water for pigs specify an upper limit for nitrates of 200 mg/L (45 mg NO_3 nitrogen/L). This water should not be used in the farrowing or weaner pens. A total nitrate nitrogen (TNN) level of 44 mg/L and a total ammonia nitrogen (TAN) of 0.5 mg/l may be tolerated. For waters used for the growth and propagation of fish, strict standards for ammonia nitrogen levels may be established, particularly when pH may exceed 8.0 and the water is to be used for sport fishing.

Question 8. Why are phosphates important?

Answer 8. Phosphorus is an inherent component of pig wastes, occurring in various forms of phosphate. Phosphates are important in environmental management because of their critical role in eutrophication.

Phosphorus is an essential element for the growth of bacteria and other organisms. Lack of phosphates prevents excessive growth of microorganisms and keeps the lake oligotrophic. Availability of phosphates in the presence of abundant sources of carbon and nitrogen causes excessive growth of nuisance organisms, such as blue-green algae, which may impart colour, taste, and even toxicity to the lake, making it eutrophic.

Question 9. What is the biochemical oxygen demand test and how is it used?

Answer 9. Biological oxygen demand (BOD) is the most widely used parameter in estimating the water pollution potential of organic wastes. It is also used in the design of aerobic processes. BOD is the measurement of the amount of oxygen utilized by microorganisms to biochemically oxidize the organic component of the waste over a period of time at a specified temperature. A measured volume of the waste sample is placed in a BOD bottle that is filled with distilled water saturated with dissolved oxygen (DO) and to which specific chemical nutrient solutions have been added. The DO level is measured initially and after 5 days of incubation at 20°C. The difference in DO levels divided by the volume of the sample is the BOD_5 of the waste. For animal wastes and wastewaters that contain live microorganisms, samples do not need to be seeded with settled sewage.

The BOD_5 of a slightly polluted stream is less than 10 mg/L; for weak sewage, it is less than 100 mg/L; medium-strength domestic sewage, about 200 mg/L; strong sewage, more than 300 mg/L.

The interpretation and use of BOD data require professional judgement based on experience.

Question 10. What is the importance of the chemical oxygen demand test?

Answer 10. Chemical oxygen demand (COD) is a measure of the oxygen required for the chemical oxidation of the organic portion of the waste. In the COD test, a strong chemical oxidant such as potassium dichromate is used in the presence of sulfuric acid. The amount of oxidizable organic matter is expressed in equivalent amounts of oxygen.

The COD test does not always include all the biodegradable organic matter, but does include organic compounds, such as cellulose, that are biodegradable but do not contribute to the immediate oxygen demand measured in the BOD, or exert an oxygen demand on a receiving stream. The BOD_5 to COD ratio in pig wastes is only 0.30. This indicates that pig wastes contain only 30% easily biodegradable organics. COD does not measure the oxygen demand of nitrogenous matter.

COD is used mainly to monitor the efficiency of treatment plants, after correlating the relationship with BOD_5 and establishing other parameters. The test can be carried out in a few hours instead of the 5 days it takes to complete the BOD test. COD tests, when carried out in a uniform manner using exactly the same technique, give more repeatable results than BOD tests, which are subject to many sampling errors and interferences. Empirical COD test procedures that require less than 1 h also can be used.

Question 11. What is the role of plankton and bacteria in water pollution and waste treatment?

Answer 11. Aquatic organisms are used as indexes of pollution by the public and by the scientific community. A good sign of gross pollution is a decrease in the variety of fish living in a body of water. Although the variety of fish species decreases drastically in a polluted stream, total biological productivity may increase.

A variety of fish, bacteria species, and other organisms means stability. Predominance of one species or of a particular type of organism (anaerobic only, instead of aerobic and facultative) implies an unstable, unbalanced ecological system. Although the public may notice pollution only when fish disappear, damage to the phytoplankton and zooplankton is worse.

Bacteria are the key to a normal biological cycle. They incorporate soluble organic matter and multiply rapidly. Newly formed bacteria become food for ciliates that, in turn, are eaten by rotifers. Rotifers are consumed by fish. Humans remove the fish for food and return waste food to the river for the bacteria. This completes the cycle. This cycle is disrupted if the waste that is discharged exceeds the capacity of bioorganisms in the river to assimilate the waste. If this occurs, oxygen is depleted, fish die, and only bacteria grow unless re-aeration brings protozoa to life to restart the cycle.

Living organisms contribute tremendously to stream recovery by using pollutants as a source of energy and growth material. Biological efficiency in a stream, however, falls far short of that in a treatment plant. Wastewater treatment plants, therefore, are designed to provide an optimum environment for bacteria growth so the decomposition process that would have taken place in a stream is accelerated and thus the organic load discharged into the stream is reduced.

One of the most common water quality parameters is the coliform test. Treatment plants are designed to reduce the number of coliform bacteria to meet effluent standards for waters used for recreation. Data on total bacteria counts can be useful in the interpretation of coliform test results. Tests for other organisms, such as fungi, actinomycetes, and nematodes, are useful both in the characterization of animal wastewaters and in their treatment.

Numbers of bacteria and fungi (measured as colony-forming units per 100 mL) in the raw wastewater flowing from the pig barns into the sedimentation tank were as follows:

Microorganism	Average number (CFU/100 mL)	Range (CFU/100 mL)
Bacteria	1.5×10^{12}	3.7×10^{8} to 2.0×10^{13}
Fungi	6.6×10^{6}	6.0×10^{5} to 4.4×10^{7}
Coliform bacteria	1.4×10^{8}	7.0×10^{6} to 9.2×10^{8}
Fecal coliforms	8.1×10^{7}	5.0×10^{6} to 5.4×10^{8}

In the supernatant effluent of the primary sedimentation tanks, the counts were as below:

Microorganism	Average number (CFU/100 mL)	Range (CFU/100 mL)
Bacteria	2.0×10^{11}	1.7×10^{8} to 2.5×10^{12}
Fungi	5.9×10^{6}	1.0×10^{5} to 5.0×10^{7}
Coliform bacteria	5.1×10^{7}	9.2×10^{5} to 3.5×10^{8}
Fecal coliforms	3.2×10^{7}	5.4×10^{5} to 1.8×10^{8}

Data from the primary sludge of the sedimentation tanks were

Microorganism	Average number (CFU/100 mL)	Range (CFU/100 mL)
Bacteria	1.1×10^{10}	1.2×10^{9} to 3.5×10^{10}
Fungi	1.2×10^{8}	2.5×10^{5} to 4.0×10^{8}
Coliform bacteria	9.7×10^{7}	1.7×10^{7} to 1.7×10^{8}
Fecal coliforms	6.4×10^{7}	1.1×10^{7} to 1.7×10^{8}

In the effluent of the high-rate algae ponds, microoganism counts were as follows:

Microorganism	Average number (CFU/100 mL)	Range (CFU/100 mL)
Bacteria	2.8×10^{7}	1.7×10^{6} to 1.5×10^{8}
Fungi	2.0×10^{4}	0 to 7.2×10^{4}
Coliform bacteria	4.7×10^{4}	2.0×10^{3} to 2.0×10^{5}
Fecal coliforms	1.1×10^{4}	0 to 5.4×10^{4}

The major group of microoganisms in all units was bacteria. Total coliforms accounted for 0.01, 0.03, 0.90, and 0.17% of total bacteria in the raw wastewater, supernatant effluent, primary sludge, and algae-pond effluent, respectively. Of these, 58, 63, 66, and 23% were fecal coliforms, respectively.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Sampling programs, procedures, and test analyses for a local feedlot to reflect local concerns and needs.
2. Design parameters and comparison with published values for the the most significant properties of pig and other livestock wastes.
3. Parameters for the measurement of water pollution and local water quality standards for rivers and estuaries.
4. Write an environmental impact assessment statement according to local requirements and estimate cost for a major animal feedlot area.

Chapter 6

Olfaction and Malodours in Pig Farming Areas

Odours play a crucial role in livestock production. This chapter describes the fundamentals of olfaction and details various studies. The concepts of malodour index gas and iso-osmic (equal odour) and isodysosmic (equal malodour) lines are introduced along with malodour management principles in an intensive PFA. The question and answer section presents opinions that should be helpful when making judgements on the matter of dysosmia (malodour) management in a PFA.

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Olfaction

Smell, like taste and hearing, is a complex process that is not fully understood. For every odorant there is a minimum concentration below which the olfactory cells are not stimulated. This concentration is called the threshold odour concentration or the minimum identifiable odour. For some highly toxic or obnoxious odours, the threshold level can be as low as parts per trillion.

The odours themselves are highly complex chemically. Animal and animal-waste odours may contain many chemical units. As a result, it is difficult if not impossible to duplicate chemically specific animal odours. It is not clearly known why some of the products in a biochemical reaction smell whereas others produced at the same time are completely odourless.

Odour Perception

It is the perception of odour that is of critical importance in livestock production and waste management. Perception of an odour is also a highly complex process. Many functions occur during perception. The nose, mitral cells, and brain are involved. The brain becomes aware of the personal significance of the odour through previous experience and innate defense against foul odours. The key here, particularly with respect to the management of livestock operations, is the previous experience of the person who smells a particular odour.

Most people living in urban centres have not been exposed to farm odours. These people perceive farm odours as unacceptable, while they may tolerate a city malodour with which they have been familiar since childhood. Generally, if an odour brings back pleasant memories, the person would most likely rejoice. If the person recalls familiar odours, they will most likely proceed without paying much attention. If the odour brings back adverse thoughts, then the person may become nervous and depressed and begin to tire easily. If the odour is new but unpleasant, then the perceiving person becomes irritated and likely complains.

Pleasantness or unpleasantness of the odour is also determined by the psychological state of the person; for example, if one is hungry, the odour of a favourite dish being cooked gives rise to a pleasant disposition. Rural people tend to be more tolerant of livestock smells, but are irritated by urban or factory smells. In urban Singapore, people are not familiar with animal smells and, thus, have low tolerance for odours associated with livestock production.

Because odours are judged subjectively, reactions to odour stimuli are not always predictable. Moreover, the sense of smell becomes selective, smelling instinctively certain odours and ignoring others. Smell, like taste, may adapt to some stimuli after exposure and become dulled with time.

Odour Interpretation

Interpretation of odours occurs after perception. The nose tends to classify odours on the basis of the source or in association with a familiar substance. Table 6.1 gives an empirical classification of livestock odours.

Pungent odours are associated with ammoniacal substances such as poultry manure and may contain amines, skatole, indole, and a host of other organics. Putrid odours are from sulfurous substances such as proteinaceous feeds undergoing septic decomposition. Rotten eggs and septic manure give putrid odours that contain hydrogen sulfide,

Table 6.1. Classification of odours associated with livestock production.

Type of odour	Most likely source in livestock production	Most likely chemical substance
Pungent	Poultry waste, urine	Ammonia
Putrid	Septic pig waste, fish meal, rotten egg	Hydrogen sulfide, mercaptan
Stinking	Rotting fish or meat, open fecal decomposition	Amines
Nauseous	Septic sulfurous waste, swill, hide tanning, rotting leather	Skatole, indole, sulfides, putricine
Musty	Stabilized manure, digested sludge	Sulfides
Fresh	Composted manure, manure mixed with hay	Skatole

mercaptan, and sulfides in combination with acids and amines. Stinking odours are intense odours typical of open decomposition of highly biodegradable organic matter such as feces and rotting fish.

Nauseous odours are heavy odours emanating from rotting flesh, leather, or swill cooked in enclosed areas. Musky odours are those that blanket an area and inundate a person's nostrils. This happens in a pig farm during a calm, humid night or near an anaerobic lagoon. Fresh odours are those associated with open-air, non-septic wastes and are common in rural areas.

The nose can smell more than one odour at a time. It is almost like listening to a symphony: one hears the orchestra as a whole but also the distinct sound of the oboe. In olfaction, one odour may mask or neutralize another. The component odours are perceived in their own individual characteristics; i.e., one could smell a pungent odour from a chicken shed and the aroma of an orchid at the same time. However, there are cases where a pungent odour may exist but cannot be smelled because it is masked by another odour. Also, the unpleasant odour may be suppressed depending on the psychological or emotional state of the perceiver.

In practical terms, the willingness of neighbours to suppress a familiar odour may mean that keeping good relations with neighbours may be just as important as the odours themselves. Farm odours could be masked with sprays of orchid scent or the strong smell of durian, a popular edible fruit in Southeast Asia. Durian grows on the stems of very tall trees and, when ripe, emits a distinct putrid smell. The odour is so pervasive that it is against the law to eat durian in hotels, offices, or any enclosed public place. However, to those who enjoy durian, their odour evokes a pleasant response. If these same people are unhappy with the presence of a livestock operation, even in the midst of durian scent, they will tend to reinforce their smell of the unpleasant animal odours by focusing on them.

Response to Odour

Maximum olfactory response occurs in the first breath. When people open a window in the morning or evening and take their first breath of air, they sense the odour much more than after several breaths. Lasting impressions may be formed on the basis of this first breath. Thus, newcomers are more apt to complain. This is why odour panelists breathe odourless air between sniffs. Total adaptation to specific odours occurs as the sense of smell becomes fatigued. People may also adapt to one odour but not necessarily to another; for example, pig farmers tolerate pig odours but dislike odours from poultry units next door, and vice versa.

Normally, disputes on malodours are settled in courts of law or by official action by government authorities. However, the laws and regulations are quite general and are based on principles of public nuisance rather than economic damage.

Socioeconomic Aspects

Socially, odours are an annoyance and can interfere with normal everyday activities. However, social effects cannot always be quantified or even verified. The complainants themselves find it difficult to describe their annoyance with assurance. Furthermore, people who complain or volunteer opinions tend to exaggerate.

The economic cost of odours may be evaluated through reduced property values, reduced productivity of workers, and reduced sales in commercial areas. Although such reductions do occur, they are not easily quantifiable. Although economic losses as a result of odour cannot be objectively measured, people perceive them not only in terms of interference with normal enjoyment of their property but also as a threat to the value of their homes. It is at this stage that official complaints and law suits are lodged.

Nuisance Laws

The common law that may or may not be legislated is that of the accepted right of a person to enjoy his or her property or public places without unreasonable interference by odours from outside sources. In Singapore, a parliamentary act promulgated in 1972 authorized the government to close down farms that created a public nuisance. Recent regulations in some countries require that operations that are potential sources of malodour obtain a licence or permit before becoming established. The licence would specify, for example, minimum distances from residential areas. Licencing neither deters people from suing nor exempts farms from being sued under the provisions of nuisance. The pig farms in Ponggol had received permits and leases to carry on pig production in an area zoned for that purpose. However, once a new town developed within a kilometre of the PFA, prevention of public nuisance took precedence over pig farm licencing.

In the United States, there have been many private suits against neighbouring livestock farmers on the grounds of odour nuisance. Most cases were decided on the basis of expert testimony by engineers and scientists who argued the merits of both sides because of the lack of objective measurable standards. Attempts have been made to set odour standards. These standards were based on dilution factors, but their enforcement was determined by sensory detection, which is subjective and, thus, still subject to expert witness testimony. Meanwhile, robots have been developed that are capable of detecting specific odours; however, their application is limited to highly prized substances of repeatable odour signature.

One approach to protecting the livestock industry from nuisance harassments is to designate a site as a livestock farming area and recognize that malodours cannot be completely eliminated. Zoning does not give absolute protection to the farmers because malodours may travel beyond buffer zones, and encroachment by private developers cannot always be prevented. However, zoning does protect the farmers from individual lawsuits. The best approach in a livestock operation is to design and operate waste handling systems that minimize the release of malodourous substances.

Noxious Gases

From the standpoint of environmental health, the most important gases generated from animal wastes are carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4). Table 6.2 lists the major properties of six significant noxious gases.

Carbon Dioxide

Carbon dioxide is an odourless, colourless gas that is heavier than air and highly soluble in water. It is found in the atmosphere at a concentration of 0.03% (300 ppm) on a volume basis.

Carbon dioxide constitutes 40% or more of the bubbles arising from decomposing wastes in pits under slatted floors or in lagoons. CO_2 levels are about 10% higher in buildings with liquid manure handling systems than in buildings with solid systems. Exposure to a CO_2 concentration of 7.8% by volume with corresponding reduction in oxygen can cause suffocation. Exposure to CO_2 concentrations above 5% (50 000 ppm) causes loss of appetite, distress, and asphyxiation if exposure is longer than 30 min. Such concentrations cannot be reached in open buildings used for livestock production. The highest level measured over slotted floors in a pig building in Singapore was 0.12% (1 200 ppm).

Ammonia

Ammonia is colourless but has a pungent odour that can be detected at concentrations as low as 0.15 ppm on a volume basis (114 $\mu g/m^3$). Because it is lighter than air, ammonia moves up from the floor and is inhaled by pigs. It is highly soluble in water, which in part explains the presence of higher ammonia odours in confinement units that use solid handling systems. Ammonia is an irritant that causes eye inflammation and photophobia (fear of light) in poultry. It tends to discomfort pigs and, at extremely high concentrations of 100–200 ppm, pigs begin to sneeze, foam at the mouth, and lose their appetite. High ammonia levels are partly responsible for tail-biting by young piglets in weaner pens. However, NH_3 levels never exceeded 50 ppm in Singapore PFAs, even under slatted floors.

Hydrogen Sulfide

Hydrogen sulfide is a toxic gas. It is colourless, but has a putrid, nauseating odour characteristic of rotten eggs. It is heavier than air and,

Table 6.2. Characteristics of noxious gases.

Gas	Molecular weight	Density (g/L)	Specific gravity in air[a]	Solubility (cm^3/100 g)	MAE[b]		Threshold odour	
					ppm	mg/L	ppm	mg/L × 10^{-3}
Carbon dioxide (CO_2)	44	1.98	1.53	90	5000	9.82	Odourless	
Carbon monoxide (CO)	28	1.25	0.97	2	50	0.06	Odourless	
Methane (CH_4)	16	0.72	0.55	47	1000	0.71	Odourless	
Ammonia (NH_3)	17	0.77	0.60	50	50	0.04	0.15–5.0	0.11–3.8
Hydrogen sulfide (H_2S)	34	1.54	1.19	250	<20	<0.03	0.001	0.0015
Oxygen (O_2)	32	1.43	1.14	3	>180000	—	Odourless	

Note: In the United States, the ambient air quality standard for H_2S is set at less than 0.10 ppm for 1 h. CO_2, H_2S, and O_2 are slightly heavier than air, which means that under calm conditions they tend to remain at floor level in a slatted floor and can be easily inhaled. CH_4 rises to the roof, where it may concentrate in an enclosed structure and explode in the presence of a spark. H_2S is highly soluble in water. One way to minimize H_2S odours is to dilute the source waste stream with water. H_2S can also be easily oxidized by free oxygen; therefore, aerating a waste stream can minimize odour.

[a] Density of air is 1.29 mg/L.

[b] MAE, maximum allowable exposure for 8 h in a work station for humans (according to the 1977 standards in USA). To convert ppm to mg/L, multiply molecular weight by 22 400 (the standard volume of a mole of gas) and divide the product by 100 000.

therefore, remains in the building unless moved by turbulence or wind. It is water soluble; therefore, the higher the dilution of manure with clean water, the greater the control of H_2S. Furthermore, H_2S can be oxidized by free oxygen in the air or by dissolved oxygen (DO) in water. Thus, dilution with air or water aids H_2S control.

Hydrogen sulfide is toxic, even at low concentrations. Because of its intense odour, the human nose gets easily fatigued and high H_2S concentrations may not be sensed readily. In acute poisoning cases, the action of H_2S is so rapid that there are few signs of imminent danger. Sudden nausea and unconsciousness are followed by death. If the amount of H_2S inhaled is sublethal, recovery can be complete, but the animal may become susceptible to pneumonia and other respiratory diseases. Animals exposed continuously to levels of about 20 ppm H_2S develop photophobia and anorexia (loss of appetite) and become nervous. Other symptoms at levels of 50–200 ppm H_2S include vomiting, nausea, and diarrhea. Measurements in an open porker barn in Singapore showed that H_2S levels did not exceed 0.5 ppm.

Methane

Methane is odourless, colorless, and nontoxic. Methane rises quickly from the floor and tends to accumulate near the ceiling in air-stagnant corners. If the CH_4 concentration is 5–15% by volume and oxygen is present, a small spark can cause a dangerous explosion. However, there is no possibility of this happening in open pig buildings.

Oxygen

When the oxygen concentration in the air is reduced from its normal 20% to less than 12% because of poor ventilation in a totally enclosed pig building and the CO_2 content rises to 8% because of animals exhaling CO_2, lethal conditions are created. Under such conditions, breathing becomes laborious, there is a loss of muscle control and consciousness, and pigs eventually die. In the final analysis, oxygen depletion is the real cause of death, but the increase in CO_2 level, heat stress, increased humidity, panic, and other factors hasten death. Oxygen depletion does not occur in open buildings.

Dangerous Situations

There is no evidence that noxious gases ever reach lethal concentrations inside confinement buildings, yet there have been animal and even human deaths in other parts of the world. In almost all these cases, death occurred when the ventilation system broke and all doors and windows were shut tight, or when liquid manure was stirred under under slatted floors without adequate ventilation.

Human deaths occurred when people ventured into a manure pit or access hole without a mask or a companion to pull them out at the first sign of danger. Two men died in Penang, Malaysia, when they entered, without adequate precautions, an access hole to repair a pump for pig wastewaters. Farmers must never enter a cesspit even if it is empty. To avoid constant exposure of animals to manure gases in totally enclosed buildings with slatted floors, forced ventilation is essential. Air should come in from the ceiling and be exhausted at or below the slatted floor.

Odour Measurement

There are two basic approaches to odour measurement: analytical and sensory or organoleptic. Olfactory evaluation is widely used for detection and evaluation of odours, but it is not selective in determining odour components. Both wet-chemical and instrumental methods are used to separate, identify, and quantify gases that emit specific odours. Analytical methods involve the chemical determination of the presence or concentration of a particular substance. However, analytical data must still be interpreted by reference to some target level established by sensory means. A combination of analytical and sensory systems is the best method, but it is cumbersome, expensive, and not always reproducible.

Before procedures for the measurement of odours can be made, the odorous substances need to be identified. With the introduction of intensive confinement livestock feedlots, cases of odour nuisance and animal death began to emerge in the 1960s. At the same time, research was initiated to identify noxious gases and the components of malodours from animal wastes.

Analytical Methods

The most common analytical instruments used are the gas chromatograph and the classic wet-chemistry procedures. Gas chromatographic methods are the most accurate but are also laborious, sophisticated, and require specialized skills and equipment. They are more amenable to research studies.

For gas chromatography, the odorous air components need to be concentrated. This can be done cryogenically or by selective absorption. The analysis in the gas chromatograph can be carried out with flame ionization detectors, electron capture, or other methods.

Wet-chemistry methods involve chemically treated inert materials, such as paper strips, on which definite colour changes occur in proportion to the gas concentration. Such gas detectors are used in mines, certain factories, and, recently, animal housing. There are limitations to these devices, mainly in precision and accuracy. Paper strips impregnated with lead acetate can be made in any laboratory to confirm the presence and relative concentration of hydrogen sulfide. However, there are several companies that manufacture lead acetate strips with precalibrated, direct-reading colour charts.

Gas analyzers may also be used. Most of these devices are more suitable for inorganic, fixed gases such as CO_2, O_2, H_2, and CH_4. However, most malodorous gases are mainly organic volatiles, readily oxidized in the presence of free oxygen. If this were not so, malodours would permanently remain in the environment.

One common analytical device is a universal tester pump that is outfitted at its inlet with chemically impregnated tube vials. The pump sucks 100 mL or more of air through the vial. Colour changes along the length of the vial indicate the concentration of a particular gas. The same manufacturers produce automated pumps that suck preset volumes of air at preset times onto impregnated strips or through tube vials. Odorous gases can thus be monitored without human attendance. The vials are calibrated for a single compound, and the concentration scale is printed on the tube for direct reading. For multiple-use tubes, calibration charts are provided by the manufacturer.

Standard chemistry handbooks and textbooks have details for individual chemical compounds. The usual procedure is to pump or suck measured volumes of odorous air through a series of chemical solutions that absorb or trap the volatile odorous components.

Sensory Methods

Testing Panel

The only practical way to measure odours is to use human testing panels. The size of these panels may vary from 3 to 30 people. Panel size represents a compromise between measurement cost and desired statistical confidence in the results. For serious cases, at least eight panelists should be used. If the panel is to evaluate odours in a community, a panel representing the economic and cultural composition of that community should be used. However, in most cases, panelists should be selected because they can differentiate among odours, focus on more than one odour, understand the test procedure, and be self-disciplined during the test because screening procedures can be quite cumbersome and time consuming.

In direct methods of measuring odour intensity, samples of odorous air diluted to different degrees with odour-free air are presented to the panel. The dilution is designed to decrease the concentration of odorant until it reaches the threshold odour concentration. Odour intensity can then be expressed in terms of the dilution factor needed to achieve the odour threshold, e.g., if 100 volumes of odourless air are required to dilute the sample to threshold, the odour intensity is stated as 100 odour units.

Odourmeters

Devices have been developed to aid sensory analyses of odours in field measurements. The scentometer is a hand-held, transparent plastic box with two clean air inlets and four odorous air inlets of various diameters. It uses two layers of activated charcoal to provide odour-free air and a series of calibrated orifices through which precise amounts of odorous air are passed. Odour samples are diluted in a chamber and then pass through sniffing ports to be evaluated by the operator. Progressive dilutions can be evaluated until the threshold is reached. Simple calculations yield an odour intensity in terms of odour units or dilutions to threshold.

The main advantage of the scentometer is its use in rapid evaluation of odour levels in actual field conditions. No problems are encountered in collecting, transporting, and preserving samples for evaluation in a laboratory. A disadvantage is the limited range of dilutions available. The odorous air may be diluted in ratios of up to 128 to 1. Other limitations of this type of device include the following:

- The sensitivity of the operator is affected by odour fatigue.
- Nostrils cannot be cleared with odourless air between observations.
- The charcoal bed can become saturated with odorant.
- Most odours are intermittent and, thus, cannot be captured in discrete grab samples.

Another field odourmeter is the direct-reading olfactometer. The olfactometer is carried on the back of the odour assessor. This person wears a gas mask and can smell different dilutions of the air being pumped through the mask. The operator is supplied with background air filtered through activated carbon throughout the measurement. During odour sampling, the operator enters wearing the face mask and sniffs samples of different dilutions, which are fixed by an assistant who operates the pumping system on the operator's back. Dilutions are achieved dynamically with battery-operated pumps. Dilutions are reduced until the minimum detectable threshold odour concentration is defined. After confirmation over several trials, the dilution needed to detect threshold odour is considered as one odour unit.

The advantages of the direct-reading olfactometer are that it is accurate and can be precise with experienced operators. However, it is costly and requires two people to operate. The scentometer is small and one-tenth the cost. Gas chromatographs are two to three times more expensive than the olfactometer.

Cotton Flannel Swatch

Cotton cloth pieces can be used to capture odours in the field and bring them to the laboratory for organoleptic examination. Swatches (about 100 mm × 100 mm cotton flannel fabric dried for 4 h at temperatures below 100°C) are suspended over the source of the odour to be surveyed. After exposure of a few hours, the swatches are placed in an air-tight plastic bag and transported into a clean-air room away from the odour source and presented to odour panelists. This technique of capturing the odour can be used to get people who lodge complaints to determine whether the odour they complained about is the same as the one originating from the source.

Threshold Odour

Detection threshold is the minimum concentration of odorant that elicits a response. Recognition threshold is the minimum concentration that can be identified. The 50% threshold is the minimum concentration at which half the panelists (or people exposed to the odour) respond to or identify the odour. Detection and recognition thresholds may be used to monitor the emission of odours and also the effectiveness of odour control systems.

Malodour Index Gases

Because there are many different volatile compounds that emit odour and because it is not possible to monitor many gases, it is necessary to identify a gas that can be used as an index of air quality. It is assumed that the concentration of malodour index gas (MIG) and the intensity of malodour are related proportionally. However, this may not necessarily be so. In addition to correlation between the concentration of the MIG and the intensity of malodour, the other criteria for selection of an index gas are ease of measurement, frequency of occurrence, stability and interactions, method of formation, and physical properties.

Ease of Measurement

Ease of measurement involves both the detection and quantification of the MIG. The test used should require little equipment and have few procedural steps, and the reaction should be immediate and not require a prolonged incubation period. Colorimetric devices such as reagent test papers are most appropriate. Devices employing an electrode measurement or some other meter reading also work, but calibration of these devices sometimes can be a problem.

Frequency of Occurrence

For the MIG to serve as a useful standard, it should occur in all similar facilities and in as many different facilities as possible. This simplifies the comparison of the odour intensity in various places.

Correlation to Concentration

MIG concentration should have a direct correlation with the amount of odour in the air. This implies that environmental factors (such as temperature or oxygen) that affect odour intensity should also affect MIG concentration. However, there is no restriction on the odour quality of the MIG. The index gas can, in fact, be odourless to humans as long as the other criteria are met.

Stability and Interaction

Stability is perhaps more tenuous than the other criteria. The gas must be stable enough so that it does not interact immediately after release from solution or before a reasonable measurement can be made. On the other hand, a gas that is too inactive is likely to be hard to measure quantitatively. Obviously, there is a large latitude between these two extremes. In general, the MIG should have the same chemical activity as the main odour-producing components being measured.

When interactions are involved, two factors need to be considered. First, the MIG should have a unique chemical nature that will allow it to be tested without elaborate isolation techniques to separate it from the gases with which it is usually associated. Second, the gas concentration that is measured should reflect any interactions that the odorants have with the environment that affect the odour quality of the air. For example, sulfur dioxide is much more irritating in the presence of water vapour than in dry air. Humidity would, therefore, be an important factor in a confined area such as a barn. Thus, if sulfur dioxide were an important odorant in a confinement facility, MIG concentration should vary to account for humidity effects. One way of correcting for such a factor is to make a standardized conversion table and relate measurements to odour intensity using the table. Thus, an index concentration of 50 ppm might not indicate the same odour intensity at 50% relative humidity as at 95% relative humidity.

Method of Formation

The MIG should be produced at a suitable point in the decomposition process. Ideally, the MIG should be produced at the same time as the main odorant. A gas that is produced as a result of side reactions or as an end product of the process is less desirable because the time lag renders correlations invalid.

Physical Properties

The MIG should be volatile at low temperatures (at least as low as the lowest boiling odorant). Molecular weight should be low because larger molecules have characteristically slower reaction rates, and reactions for smaller molecules tend to be more quantitative.

Hydrogen Sulfide as MIG

Hydrogen sulfide (H_2S) reflects anaerobic conditions, under which sulfate ions are reduced to sulfide ions. The equilibrium for H_2S, HS^-, and S^{2-} is pH dependent. At pH 8 and above, reduced sulfur exists mainly as HS^- and S^{2-}; H_2S is negligible. At pH levels below 8, the equilibrium shifts rapidly toward the formation of un-ionized H_2S and is about 80% complete at pH 7. Therefore, at pH 7 or lower, the partial pressure of H_2S becomes great enough to cause serious odour problems whenever sulfate reduction yields a significant amount of sulfide. Pig waste pH is between 6 and 7, the most favourable range for H_2S release.

Ammonia as MIG

Ammonia is a suitable MIG to monitor pig waste treatment processes because it is one of the first products to be released as the process goes from aerobic to anaerobic conditions and it is significantly reduced as conditions are reversed.

Other MIGs

Two other gases, skatole and indole, which are by-products of anaerobic decomposition, are suitable MIGs. Their odours can be absorbed on cloth materials. This property was used in the cotton flannel swatch method of odour identification in the Singapore PFAs.

Odour-Producing Conditions

Animal wastes are in an anaerobic state when excreted and remain so unless oxygen is introduced mechanically or added in oxygen-saturated water or bedding material. Under aerobic conditions, the waste is odourless. If any odours are released, they are earthy and not offensive. Under anaerobic conditions, offensive odours are generated that become worse as fresh waste becomes septic as a result of putrefaction by saprophytic bacteria.

Bioengineering parameters affecting odour production are temperature, pH, electrode potential (E_h), and aeration. In a biological system, these parameters are interdependent.

Greater amounts and more offensive odours are produced during the decomposition of animal wastes at high temperatures. This relation between odour production and temperature is in part due to increased vaporization of odorous gases at higher temperatures, but is also due to the increase in biological reaction rates, including enzyme activity, with increases in temperature.

Hydrogen ion concentration (pH) influences the activity of microorganisms and enzymes. The optimum pH for amino acid decarboxylation is 4 to 5, and this releases malodorous amines and sulfur compounds. Deamination occurs at a high pH and leads to the release of ammonia and organic acids (e.g., acetic, propionic, or butyric), which can also be malodorous.

Anaerobiosis proceeds with the reduction of organic material. Low E_h is characteristic of anaerobiosis and, in many cases, the intensity of an odour is proportional to the degree of negativity. An E_h between –265 and –295 mV produces good methane bacteria activity in sludge digestion.

Malodorous gases are generated by pig production facilities (feedmill, feed, alleys, floors, and pigs) and by animal wastes stored under anaerobic conditions. In confinement buildings with inadequate ventilation, noxious gases may become a hazard to animals and humans.

Odour Travel

Odorous compounds are transported in the air that passes over the odour sources in the pig farm and through aerosols and particulate matter.

Odorous gases are transported by wind; however, the concentration at which they reach a point beyond the farm depends on many climatic factors. Relative humidity, temperature, sunshine, wind speed and direction, turbulence, and atmospheric stability play key roles in odour transport.

In tropical climates, inversions do not persist over many days, but isothermal conditions at ground level can occur, particularly at night, as a result of radiational cooling of the ground. During an inversion, there is no vertical mixing of the air. As a result, odours build up and move horizontally to neighbouring areas. Urbanization causes more frequent local inversions.

The worst climatic condition for odour travel is low wind speed. In such conditions, relative humidity and temperature rise, favouring odour formation and travel.

Travel of odorous gases is affected by air motion and turbulence. Odorous gases are diluted to a much greater extent when they enter a turbulent wind stream. At extremely low velocities, odorous gases may travel in a laminar flow pattern without much diffusion. Thus, during calm days, these gases may reach a downwind point at a concentration not much less than the concentration at the source.

Generally, the lowest odour nuisance level occurs at high wind speeds. Normally, wind speeds are at their highest and relative humidity is at its lowest around noon. Therefore, one can expect fewer odour problems at this time than in the evening, when winds die down and relative humidity increases.

Malodour Management

There are physical, biological, and chemical methods of malodour management, but elimination of malodours is impractical.

Physical Control

Because concentration is the key to odour detection, one way to abate malodour pollution is dilution. Wastes diluted with water are less of a nuisance than undiluted wastes. However, the dilution must be such that odour concentrations are reduced below detectable limits. This would require excessive volumes of fresh water. A good thunderstorm, however, provides considerable dilution and also removes from the air particulates and aerosols that can carry odorous volatiles.

Dilution of the odorous gases in the air is also a good malodour abatement technique. However, very little can be done in open buildings to provide good roof ventilation. High winds help provide high air dilution. Because wind speed increases with height, releasing gases high above the ground would aid in malodour dispersion. Another good idea is to wash pig houses around noon to take advantage of the dispersive capacity of midday winds and sunshine.

Biological Control

The best way to control malodours is to maintain aerobic conditions throughout the period of waste handling (from excretion to final disposal). Aerobic conditions can be approached with high-rate algae ponds and mechanical aeration in ditches with slatted floors. Both of these systems were tested in Singapore. Gas samples taken below the slatted floor in an aerated pit in open buildings produced no traces of malodorous gases.

There are also deodorizing additives. Some of these additives are biological in nature (mixtures of enzymes and microbial nutrients). Most of them contain chemicals or extracts from plants or animals.

Chemical Control

Masking

In masking, a strong but tolerable odour is spread over the malodour source at concentrations high enough to mask the malodour. Because the masking agent is a strong odour, it could become a source of irritation over a long period. Masking agents also oxidize or disperse and, therefore, can only be a short-term solution. Furthermore, masking agents tend to focus on the problem, which otherwise might go unnoticed by a number of people. Masking agents are chemicals, pine resins, or mint odours. Masking agents can be purchased in aerosol or powder forms and can be spread either mechanically or manually. Masking agents are most effective when they are used at the source of the odour and, as such, are not very applicable on pig farms.

Counteraction

In counteraction, the malodour is combined with another malodour or chemical gas, to produce an odourless gas. This method is only practical when the source of the odour is one chemical compound. It is an impractical and unrealistic method for pig farms.

Sorption

Sorption is a widely used process for odour control in buildings, water treatment plants, and even wastewater plants. Odorous gases or liquids are filtered through a layer of material that has a high absorptive capacity. Activated carbon is one such material. For such a system to work, the malodorous air or wastewater stream must be very dilute.

Oxidation

Oxidizing agents, such as hydrogen peroxide, potassium permanganate, paraformaldehyde, ozene (orthodichlo robenzene) chlorine, and ozone, can be used to control malodours. Cost and practical considerations rule out widespread use of these chemicals on pig farms except for short durations or in emergencies. If disinfection of the wastewater is as important as deodorization, then their use can be justified.

Additives

Deodorizing additives are usually proprietary mixtures of chemicals and plant extracts, dried bacteria, or dried enzymes. Claims for these products range from "reduction of odour problems" (which can mean anything) to "reduction of ammonia" (which can probably be verified, but the degree of reduction or duration is not always specified). Many scientific studies have shown that these products may not be worth their cost.

Public Relations

The most important dimension of an odour is its acceptability. This can best be promoted through good public relations, including recognition of the problem, demonstrated willingness to do something about it, efforts to try suggestions made by complainants, and efforts to educate the public on the significance of the livestock industry and the implications of its elimination.

Malodour Surveys in the Ponggol Phase II PFA

Research on the identification and control of odours was not included in the plan of work until after Phase II was initiated in the Jalan Kayu area of the Ponggol PFA. One of the reasons odour studies were not included was that such work can give visibility to the problem. It is customary to assume that benign neglect of odour problems from an essential industry such as livestock farming may be the best approach. Presumably, the government felt that odour problems would not be insurmountable with a buffer zone of 300 m, as was required by the environmental regulations at the time.

Trees and bushes were planted in the buffer zone to reduce the visibility of the farms. It was assumed that local residents would tolerate the odours if they were sufficiently moderated. This assumption was reinforced by the fact that no major complaints were received in Ponggol during the construction of Phase I PFA. However, it should be noted that the people who lived around the Phase I PFA were mostly rural people who were keeping chickens and other animals within their housing compounds. Once a new town of public housing was created within 1 000 m of Phase I PFA, malodour complaints began.

In 1977, when Phase II began with the construction of pig houses in Jalan Kayu in direct view of urban dwellers, acrimonious complaints began and never ceased. Malodour studies began immediately and were completed in 1979. Meanwhile, the government halted the construction of new farms in 1978 at the Jalan Kayu PFA, and all pig-rearing activities ceased in 1985 after the resettled farmers were compensated.

Malodour studies had the following objectives:

- identify and define the odour sources and nuisance areas,
- measure the malodours,
- evaluate the extent of the problems caused by the malodours,
- develop odour amelioration and management techniques, and
- develop specific recommendations for the design of Ponggol Phase III PFA, which had been temporarily delayed.

Monitoring Hydrogen Sulfide

Paper filter strips impregnated with lead acetate were prepared in the laboratory and posted at 55 locations in the Phase II PFA in the Jalan Kayu district. The test solution was as follows: 500 mL distilled water, 100 mL glacial acetic acid, 450 g lead acetate, and 350 mL glycerine. Approximately 0.5 mL of this solution was applied to 15 cm × 3 cm strips of Whatman chromatographic paper, which had an inert base and white background. The strips were dried in a desiccator and stored and transported to the test site in airtight plastic bags.

The strips were exposed for approximately 24 h except on weekends when exposure time was 72 h. Monitoring was carried out over 3 weeks from early October to early November. The strips were protected from rain by inverted plastic cups. The colour of the strips was recorded daily on a scale from 0 (white) to 5 (brownish black). The observer also recorded any type of odour detected at the sites either as "pig odour" or "other."

Results of Malodour Studies

Hydrogen sulfide measurements tended to be high wherever there was motion of the liquid. When measurable H_2S could be detected over the middle of a cesspit, H_2S could always be detected over the overflow weir of the same cesspit.

Pig smell was detected at many points within the estate, often without H_2S reaction. However, no point gave a consistently strong odour.

H_2S strips were useful for the detection of pig waste smell, but did not give a clear picture of pig farm odour intensity. The paper strips could detect approximately 0.5 ppm or 750 $\mu g/m^3$ of H_2S, whereas the minimum detectable threshold concentration for the human nose is 0.001 ppm (1 ppt or 1.5 $\mu g/m^3$). The strong smells arising from the drain and mudflats were due to the flow of liquid, which released H_2S as it moved.

Capture of Pig Odours

Cotton flannel swatches were used to record and capture typical pig odours.

Procedure for Cotton Swatches

Cotton flannel fabric was torn into 0.5-m^2 pieces and stored in a sealed plastic bag. On the day of the experiment, smaller swatches (0.25 m^2) were prepared and hung over the odour source. After exposure, the fabric swatches were torn into 10 cm × 20 cm swatches, labelled with a code letter, placed in plastic bags, and grouped into four sets of three swatches each. Each set consisted of two identically exposed swatches and one that was different. The sets of swatches were presented to an odour testing panel the same afternoon.

Odour Testing Panel

Over 50 staff (clerical, professional, and workers) at PPRTI were used as testers. They were organized into panels of 8 to 12 people. Each panel member was given a set of three swatches to smell; two were from the same point. The panelists were required to identify the swatch with the different odour. A chi-square analysis indicated that to be 90% confident of the correctness of the panel, 5 of 6, 6 of 9, and 8 of 12 panelists had to give the correct response.

Experimental Results

The first series of exercises resulted in the following major conclusions:

- Panel members could clearly distinguish the odour of an active cesspit from a well-managed partially slatted floor.
- Panel members could separate the swatches exposed in a concrete solid floor typical of Phase I and II PFA small farms from the swatches hung in a well-managed commercial barn with a partially slatted floor.
- Panelists could not distinguish the odours captured in fabric swatches hanging over drains or in swamps, which were found to be less intense than the pig farm odours.
- Panelists could easily distinguish the odour from swill cooking (which was banned in Singapore in 1981).
- Panel members could distinguish the odour of a fresh slurry from that caused by wastes stored for several days (storage of wastes caused an odour change, but there was lack of agreement on which odour was more offensive; this test was used to see if the cesspits were the main source of odour, as most people thought.)
- Panel members could monitor the change in odour in cesspits that were covered with different types of permeable covers to reduce the release of noxious gases (grass covers made of a 5-cm layer of freshly cut grass on a wire mesh support proved effective in reducing odours but lasted only a few days).

- Panelists could differentiate between two farms with different management and waste-treatment practices.

It was concluded, therefore, that the cotton flannel swatch method was sufficiently accurate to identify odours from different sources on a pig farm and to monitor changes in odour as management practices changed.

Another major conclusion of these studies was that the source of malodour nuisance was the pig pens themselves rather than the cesspits. The feces spread on the pen floors and on the bodies of the pigs represented large surface areas that emitted odours. Based on this logic and the series of tests with the cotton swatches, it was concluded that the two farms closest to the residential areas were responsible for the odours and thus they were monitored in detail.

Dunging Pattern

A study was initiated to determine whether there was a pattern in the dunging habits of the pigs and whether this pattern could be altered or affected by the method of feeding, the shape of the pen, the frequency of pen cleaning, or the method of cleaning. All farms in the Jalan Kayu PFA were asked to cut weeds, plant shrubs, and maintain a clean environment around the farms. However, specific changes and studies were made on the two farms that were located nearest to the affected residential estate.

Field measurements were carried on the two problem farms to determine the dunging pattern of the pigs. The average floor area covered by dung was about 20%; in some pens the manure occupied about 40% of the area, in others, only 10–15%.

Because it was postulated that the larger the surface area covered with dung the larger the odour problem, attempts were made to reduce the area of the pen soiled with manure. Floor feeding was tried first in the hope that this would entice the pigs to keep the feeding area clean and to defecate at the other end of the pen. It did not work. The pigs continued their previous pattern. Observations of weaners showed that new pigs establish a dung pattern within 1 day of being put in a pen.

In another experiment, sprinklers were placed at the back-end of the pens to maintain a wet strip along the pen fence, to try to entice the pigs to defecate in a prescribed area, and to cool the pigs with the sprinkled water. The pigs ignored the sprinkler and continued their original pattern.

To establish the most appropriate time to hose down the pens to reduce the potential size of the odour-emitting area, experiments investigated the times that pigs defecated in relation to their feeding time. The usual practice was to cool the pigs with the hose, clean the pens, and then feed the pigs. This had the advantage, presumably, of cooling the pigs so that they would eat more and of removing the previous day's accumulation of wastes on the pen floors and on the body of the pigs. However, this practice was not conducive to good odour control because wastes were allowed to remain in the pens for a day. Wastes should be removed soon after defecation, if odour control is the primary concern. But the question remained: how long after feeding should the pigs and pens be hosed?

Pigs defecate most often after feeding early in the morning. Thus, the farmers' practice of hosing the pen floors before feeding in the morning made odour production worse. The waste remained on the floor during the hot period of the day to decompose and release odours. The best time to clean the pens would be late in the afternoon, around 1600, when over 90% of the wastes would have been produced and the best conditions for odour travel would have been reached. Farmers were asked to carry out such a program but did not cooperate because it was not practical for them.

The rate and pattern of dunging depended on the age of the animal (Fig. 6.1) and its habits after weaning. Odour management, therefore, would be easier if the pig producers were divided into two groups: those who produce piglets and those who fatten them. Each group could then be assigned a different time for washing to minimize the time that wastes were exposed to air. Feeding at two different times, 0730 and 1130, instead of 0730 and 1600, did not improve the situation. The percentage of floor area covered with dung at 1730 was unchanged.

Stocking Density

The usual stocking density was about 1 SPP/m^2. Because of the high

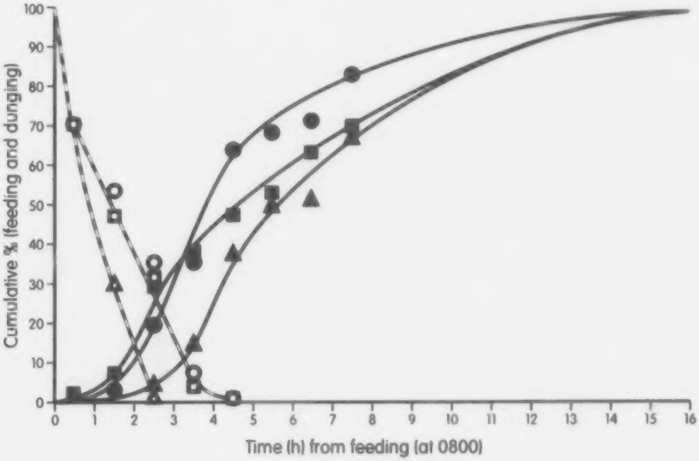

Fig. 6.1. Dunging (solid lines) and feeding (dashed lines) patterns of 30-kg (□, ■), 50-kg (○, ●), and 80-kg (△, ▲) pigs. Large pigs (80 kg ALW) tended to finish their feed quickly: 50% consumption within the first hour (100% within 1.5 h). Smaller, younger pigs ate slower, finishing all their feed within 4 h. The pigs were first fed at 0800. The defecation rate was faster with the younger pigs. Small pigs began to defecate soon after starting to eat; larger pigs began defecating 1 or 2 h after feeding was started. In a twice daily feeding regime, the pattern would have two peaks.

temperature and relative humidity, the pigs would lie down and rest quite often. When the pigs were young, they kept one area of the pen for dunging. However, this was not practical with large porkers because the farmers did not increase the area per pig with time. Large porkers cover themselves with dung, thus increasing the odour-emitting surface. It was noted that when the number of large porkers was about six per 9-m^2 pen (1.5 m^2/SPP), the pigs remained clean.

Pen Washing

The farmer in one of the problem farms was asked to wash the pig pens twice a day (at 0700 and at 1500) and feeding times were set at 0730 and 1600, 30 min after washing. This was necessary because the farmer was floor feeding and the pen floor had to be clean before feeding.

Furthermore, a high-pressure cleaner was used to try to improve the standard of cleanliness and thus reduce odour emission. The high-pressure hose dislodged a lot of fine particles from the rough surface of the concrete. However, it was too slow: by the time a barn was completed, its effect on odour was wearing off at the other end of the barn. Therefore, no estimate could be made of its effect on overall odour emission.

Conclusions

It was difficult to decrease the odour emission from the problem farm. Because management practices could not be changed, it was decided that the best solution was to resettle these farms.

Surveys of Residential Areas

Odour surveys of residential areas were carried out mainly in the evening hours. After sunset, winds would die down, traffic would subside, and people would be at home as "malodour puffs" invaded the interior of the residential areas. By investigating the pockets of odours in relation to where they were observed in the residential areas, and by tracing their origin, a most intriguing conclusion was reached: the PFA was not acting as a single massive odour source, as had been assumed; rather, individual groups of farms emanated the specific odours that penetrated specific residential areas. This conclusion, coupled with the knowledge that the pig pens were the source of the odour, shaped future research.

Survey along PFA Boundary

Odour surveys were carried out systematically for 6 months from October 1978 to May 1979. The first survey (about 1 month) assessed the effectiveness of the change in the management practices of the two problem farms previously discussed. These farms were located less than 300 m from a dense residential area south of the PFA.

Odour monitoring during the day gave an indication of the relative strength of the odour from the farms, but it did not always relate to the odour perceived in the evening. Weather had an important influence, and often changed in the evening.

Survey by Residents

Additional evening surveys were carried out by observers who walked along the streets and by cooperating residents who recorded the time and duration they sensed a smell. The group was chosen to cover the whole residential estate. The odours reaching the residents appeared to last from a few minutes to 2 h. The odours seemed to come in "puffs," which could have been caused by smell fatigue or by localized wind gusts. The times of the observations were correlated to wind direction and velocity.

Residents said the smell was stronger after a rain; however, only 25% of the reports of odour detection were after a rain. In total, 67% of the reports were during times of high humidity. From the information given, it was not possible to say whether the intensity of malodour was higher after rain.

The frequency of odour observation changed with time. This could have been due to weather changes compounded by interest or boredom on the part of the residents. Odour was produced throughout the day from the farms; therefore, the time of odour observation seemed to be governed by good conditions for odour travel. The major factor was low wind velocity; above 2 m/s there was probably enough turbulence to cause mixing and dilution of the odour. The traffic on the roads also likely caused mixing during the daylight hours. Only a part of the residential estate was affected at any one time.

Survey of Odour Travel

There are inherent disadvantages to using volunteer residents to detect malodours in the estate. The most obvious is that a nil response could mean either no odour in the region or the resident was absent or did not record the odour. To overcome this and associated problems, a program was set up to use staff to monitor odour travel deep in the estate.

Three observers were in place each evening from 1900 to 2300. Two walked while the third person covered the residential estate in a car. This pattern was followed from 18 April to 18 May 1981. For the last week, the time was changed to cover 2100 to 2400 because stronger smells developed at about 2300. If any malodours were observed, the position was marked on a map and the weather conditions were recorded. Where possible, the area covered by the odour was mapped. The results from each evening were transferred to a map of the estate to chart the overall pattern.

All observers reported very faint odours. "Odour puffs" were noted approximately 2 of every 3 days. Most of these "odour puffs" were of short duration (a matter of minutes), but occasionally the smell lasted for longer periods. There were no widespread odours from sources other than pigs during the monitoring period, but occasional local effects gave rise to false reports by residents. On two occasions, the sewage-treatment plant nearby gave rise to an odour that traveled approximately 100 m. Household garbage left out at night sometimes gave off strong smells that affected one or two houses. The overall pattern of smell for each evening, and the weather conditions, showed that the pig odour observations could be assigned to eastern or western odour sources. Plots of the distance from the presumed source against the number of observations indicated the relative frequency with which that odour would travel. The walking observers tended to report a higher incidence of odours than the person in the car because they were present at one spot for a longer period.

Figure 6.2 shows iso-osmic lines from the two main sources of odour. The term *iso-osmic* was coined from the Greek words *iso*, meaning equal, and *osmi*, meaning smell. Perhaps a better term would be *isodysosmic*, from *dysomia*, which means smelling bad. Iso-osmic lines were determined by the number of times pig odour was detected at the site. The direction of the wind was used to identify the odour source.

Malodour Abatement

Because the largest source of pig odour was the pig pens themselves, an experimental barn was designed with slatted floors and a flushing system. Flushing was designed to move the waste from the barn to the lagoon as soon as possible after defecation to minimize odour-producing conditions.

Flushing and Slatted Floors

Partially slatted floors, a lagoon, and a pump to recycle lagoon water for flushing under the slatted floors were tested on one farm that built new facilities. Wastes falling into a specially designed channel with a 1% slope were removed by water flushed down from a siphon tank. The flushed wastewater was treated in a lagoon and recycled through the siphon tanks. Based on data with cotton flannel swatches and other measurements, it was concluded that a slatted floor with flushing was much better than a solid floor for odour control.

The potential for odour production through the recycling of the lagoon wastewater used to flush the pig pens was monitored for 6 months. Table 6.3 gives the results of ammonia measurements. Ammonia levels in the air 2 m above the floor averaged 1.15 and 0.42 ppm in the weaner and porker pens, respectively. Below the slats, weaner- and porker-pen concentrations averaged 6.0 and 7.5 ppm, respectively. Ammonia concentrations were below 1.0 ppm most of the time in the weaner pens and all of the time in the porker pens, indicating excellent odour control.

Ammonia levels under the slats decreased soon after the flushing system was started in January 1979. In early March, the lagoon aerator and recycle pump were shut down and the pig pens were not flushed. Soon after, high ammonia concentrations of 17 and 19 ppm were measured in the space below the slats. Within a month after restoration of aeration and flushing, ammonia levels decreased to below 5 ppm. The ammonia levels in the weaner pens were slightly higher than in the porker pens because the weaner pens were flushed only every other day; porker pens were flushed daily. Furthermore, the feed for the weaner pigs was richer in protein and produced more ammonia.

Lagoon Aeration

Amelioration of the odour from the lagoon itself was also studied. Hydrogen sulfide detection strips were placed around the lagoon and

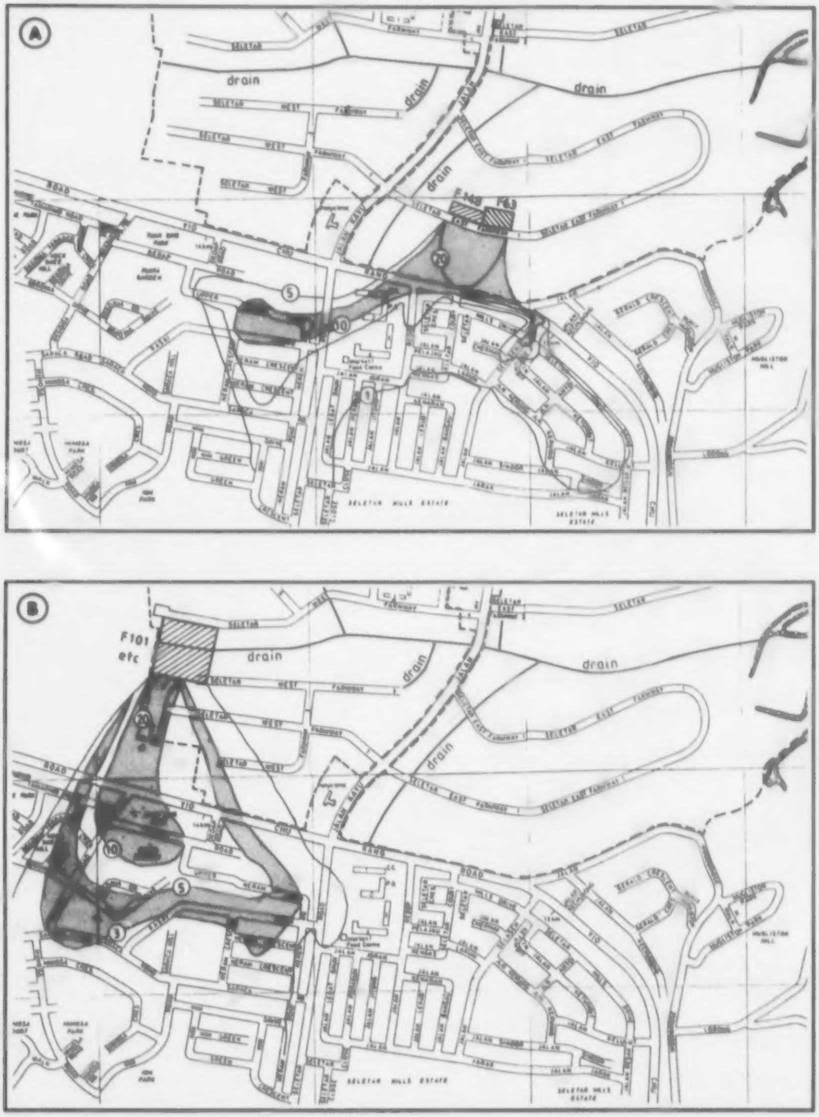
A
drain
drain
drain
F148
F63
20
5
10
1
B
F101
etc
drain
drain
drain
20
10
5
3

Fig. 6.2. Iso-osmic contour lines from two PFA sources. The scale of the iso-osmic lines ranged from 1 for a faint odour to 20 for a strong malodour: (A) iso-osmic contour lines that were attributed to farms F148 and F63 (the two problem farms) as a single source; (B) iso-osmic lines from another PFA (F101).

Table 6.3. Ammonia levels (ppm) in porker and weaner barns equipped with a flushing system.

Date (1979)	Weaner barn		Porker barn	
	Above slats	Below slats	Above slats	Below slats
3 Jan.	0.33	10.0	0.70	6.5
4 Jan.	0.55	5.3	0.44	10.0
11 Jan.	0.44	6.0	0.22	4.7
25 Feb.	1.50	2.0	0.22	2.0
8 Mar.	0.56	17.0	0.33	19.0
8 Apr.	3.40	0.7	0.56	4.0
6 June	1.30	1.3	0.44	6.0
Avg.	1.15	6.0	0.42	7.5

monitored over a period of several months. Hydrogen sulfide was detectable when the lagoon operated as an anaerobic system. However, when surface aerators were installed, no H_2S was detected, except when the aerators were shut down for repair or for experimental purposes. The H_2S concentration was below 0.025 ppm. Ammonia concentrations measured downwind from the lagoon ranged from 0.2 to 1.5 ppm, with an average of 0.7 ppm. The concentration did not vary with time. Slightly higher concentrations were detected when the lagoon was loaded with fresh wastes. The observed concentrations of ammonia were much lower than the lowest threshold limit of 5 ppm, and were of the same order before and after aeration.

Acetate strips were used to compare H_2S emissions from the lagoon before and after the installation of the aerator. A significant colour difference could be seen in the strips before and after aerator installation. The strips exposed before installation were darker; when the aerator failed, the strips exposed during the failure periods were also darker. This showed that there was a definite reduction in H_2S emissions from the lagoon when the aerator was in operation.

Cesspit Aeration

A three-compartment cesspit was aerated with a jet aerator equipped with a propeller at the end of the jet shaft. The aerator was powered by a 3-hp (2.2-kW) motor. During the first few days after the aerator was started, there was foam in the aerated compartment. The foam carried many solids with it and overflowed the end walls of the pit for a short period. The liquid in the aerated compartment became odourless during the aeration phase. Ammonia level fell from 8 ppm to less than 5 ppm. Aeration did not reduce the amount of solids discharged.

Cesspit Solids

To improve the effectiveness of cesspits in degrading solids, the contents of a two-compartment cesspit were agitated with a 2-hp (1.5 kW) submersible pump. The pump was not a good mixing device, although the effluent was improved when an effective baffle was added. However, in general, the cesspits were inadequate. Suggestions to improve their performance were made but all were impractical to implement.

Based on the investigation of existing cesspits in Ponggol Phase I and in Jalan Kayu PFA, a review of related literature, and the interpretation of data collected from sampling and experimental tests, the effectiveness of cesspits in odour control could not be ascertained because the processes involved could not be controlled. However, baffles to prevent floating solids from leaving the cesspit effectively reduced pollution.

Relevant Findings from Odour Studies

Odour Measurement

Swatches

Cotton flannel swatches were adequate recorders of odour intensity and quality for panel evaluations.

The odour absorbed in a pig barn was similar to the one experienced by residents who lodged complaints. Cesspit odours were recorded as relatively strong, but were not similar to the odour experienced by the residents in the housing estate.

The drain and mangrove swamp odours were less intense and could not be identified readily by panelists.

Impregnated Papers and Vials

Both the papers and vials impregnated with chemicals that changed color in proportion to the concentration of odorant compounds were found to be reliable.

Odourmeters

Both the hand-held scentometer and the large, direct-reading olfactometer are cumbersome to operate but both can be useful tools for odour measurements, particularly for setting iso-osmic standards.

Panels

Both field observers and laboratory panels were found effective but were very difficult to manage because of the large number of people involved.

Factors Influencing Odours

Various factors influence odour as perceived in the vicinity of a pig production area. The magnitude of the production and the degree of concentration are important. The Jalan Kayu area was planned for a large swine population in a confined area. Thus, by comparison with other countries and particularly with metropolitan areas, this was a highly concentrated PFA next to a highly concentrated, middle-class residential estate.

Climate also influenced odour levels and odour transport. High temperatures, high humidity, and low wind velocities increase odour production and perception. All three of these factors existed in the PFA and made odour control more difficult. Furthermore, no single wind direction prevailed. The local weather was affected by northeasterly monsoons from October through December and by southwesterly monsoons from March through May. The intermonsoonal periods were characterized by localized showers and winds.

Design and management of the production facilities also affect the odour transmitted to surrounding regions. This was the area in which the greatest potential existed for odour control. Specific aspects of the production system that have an odour impact include feed processing (particularly swill cooking), the animals, and their feces and urine. Based on these findings, farm layout and pig production facilities were redesigned for the third phase of PFA development.

Production Facilities

Farmers cleaned pens daily with a water hose, and open gutters were used to transport manure from the buildings to cesspits. The cesspits had never been emptied and were operated like open septic tanks.

Pen design was relatively standard at approximately 1 m^2/SPP. Most pens sloped to a waste collection gutter but not all had an adequate slope. Slatted floors were a part of some of the facilities, but there was no specific provision for removing the manure from beneath the floor.

The amount of floor space per pig was an important variable. Low densities required excessive investment per pig produced and generally led to dirty animals. At high densities, animal stress was observed.

Waste Management

Inappropriate gutter design was the most common cause of strong odour. Some gutters had a low edge opposite the pens that allowed manure to be washed across the gutter into a nondraining area. More commonly, gutters had too little or no slope, which caused manure to stand in the gutters and decompose. Gutter odours can be minimized by proper design that prevents spillage, facilitates drainage, and prevents manure hold-up along the sides. Gutter flushing following daily pen washing is necessary but was not practiced.

Cesspit design was another area in which engineering input was needed to improve their function as solids-removing devices and to reduce their odour. The most immediate need was for a scum guard at the outlet to prevent the escape of floating solids. This scum guard also had the potential to produce a scum on the surface of the cesspit that would help reduce odour. Access to the cesspits for solids removal was also important.

Landscape

Proper landscaping to prevent standing water, particularly manure-laden water, contributes to odour control and creates a more esthetically pleasing environment. Building and drain layout is also important to facilitate vegetation control so as not to impede liquid flow or block the movement of solids.

Trees were planted along the south edge of the Jalan Kayu PFA, screening the pig farming activities from those who saw them as odour-producing rather than food-producing stations. Two activities that were considered but not tried were

- aerial sprays along the full length of the bush buffer screen to test the odour-absorbing capacity and capability of a wet screen and
- incorporation of odour-masking agents or strong familiar aromas to test the reaction of the residents and the acceptance of this practice.

Odour Sources

Four sources in the PFA contributed to overall odour production: production pens, feed, cesspits, and drains. Each was subject to individual steps for odour reduction, although it was not easy to assess the importance of each source.

Pen Floor Area

In an intensive swine production area such as Jalan Kayu, pig feeding floors comprise the greatest single odour-generating surface. Floor surface was 40 to 60 times that of the cesspits or drains, the next two largest surfaces. If the surface area of the animals was added to the area of the floors, the odour-generating surface became larger than the cesspits by a factor of well over 100. Thus, design and management techniques that promoted a minimal amount of fecal material on floors and on animal skins were important in terms of odour control. Fortunately, many of these techniques also lead to improved economic return. Because many of these management factors had not been evaluated in tropical climates, the opportunities for management-based engineering studies were evident.

Swill Cooking

Feed storage and processing contributed to the character and intensity of the odour. Dry commercial feed produces little odour directly; however, storage, cooking, and handling of garbage swill did create odours. A number of producers fed cooked food waste (swill). Although odour was produced, no better use could be made of the waste food because swill feeding helped reduce the waste disposal in the whole country.

The swill was cooked slowly in open kettles heated by burning scrap lumber. The process released distinctive odours. On farms in Jalan Kayu, the cooking areas were roofed. Once cooked, the swill was transported manually to the pens. To control the release of odours, vapour from the cookers would have to run through a condenser or air scrubber. This would involve fabricating covers for cookers, building vapour-collection systems, and fitting the stream to a small condenser and scrubber. Although there were commercially available condensers and scrubbers, they were generally much larger than needed for a swill cooker. For this reason, but mainly for disease control, swill cooking was banned.

Cesspits

The cesspits acted as open septic tanks and released a strong odour of decomposition. Because of their relatively small surface area, they were not considered the major odour source. There was no provision for removing solids from the cesspits; therefore, odour intensity was likely to increase with time. Odour was also expected to increase during periods of infrequent rainfall. As the cesspits filled with solids, more solids escaped and were deposited in the drains and the upper reaches of the estuary. During dry weather, when drain flow decreased, there was less flushing of the upper reaches from the cesspits, all of which overflowed to the public drains. The volume of the cesspits was 0.15 m^3/SPP, which would provide solids storage for approximately 35 days. As the tank filled, its effectiveness as a solids remover decreased. Eventually, the same quantity of solids was leaving as was entering the pit, except for those liquified as a result of anaerobic biological activity.

The warm temperatures of the tropics and the ready availability of energy in the organic matter for anaerobic microorganisms meant there was extensive anaerobic activity within the cesspits. This promoted some turbulence as gas bubbles were released in the anaerobic process of decomposition.

Waste Disposal

The standard waste-disposal scheme was to hose feces from the buildings to a cesspit designed to remove the settleable fraction of the manure and to allow the liquids to flow into public drains and hence into estuaries along with other waste effluents. This system had the potential for both odour and water pollution problems.

Cesspit overflow entering the public drains carried significant quantities of solids, which accumulated as sludge banks in the drains and in the receiving watercourse. At some spots, the clear odour of swine manure could be detected. This produced an odour source of considerable surface area whose frequent turbulence promoted transfer of odorants from the liquid to the gas phase.

The key to reducing odour and water pollution from the cesspits was to regularly remove solids. The most desirable solution would be an economically attractive use for the solids. As a feed ingredient, there was little potential after it had undergone anaerobic decomposition. To preserve the feed value, prompt recovery and processing would be necessary and this would be particularly difficult for small independent pig producers. Eventually, it was decided to ban the use of cesspits.

Drains

Within the Jalan Kayu PFA there were approximately 2 km of open public drains that carried both cesspit overflow and other locally generated wastewaters, including effluents from domestic sewage-treatment plants.

The drains were designed to also carry stormwater. Assuming a dry-weather width of 1 m, this surface area was roughly equal to the entire surface area of all the cesspits in the PFA. In addition, considerable turbulence was induced by weirs and grade changes. Actual measurements showed elevated H_2S and odour levels in the vicinity of the drains. However, drains such as these are common in tropical areas like Singapore, and the Jalan Kayu drain may have been no more odorous than others.

The public drain had a small section at the bottom for dry-weather, cesspit effluent flows. An idea that was considered was to cover the V-shaped channel in the centre of the drain to inhibit escape of volatiles during dry weather; the cover would not be a constraint during high flow conditions.

Another way to reduce odour from the drain would be to improve the quality of water entering from the cesspits. Another option would have been to use the drain as a raw waste drain and provide a single treatment facility at the lower end.

Odour Travel

Odours from the pig farms at the Jalan Kayu PFA traveled into the residential areas downwind from the PFA.

Time of Travel

Odours were most frequently encountered in the late evening and early morning when air movement was from the north with a velocity of less than 1.2 m/s.

Nature of Travel

Pig odours were intermittent and occurred as "odour puffs" at various sites within the residential area; however, at times they would occasionally blanket the whole area.

Duration of Malodours

The odours lasted for a few minutes to a few hours within the residential area. Occasionally, a more wide-spread, longer lasting odour developed and blanketed the entire PFA.

Penetration of Odours

Deep penetration of odours into the residential estate was infrequent. This may have been due to dilution with distance and have been aided by traffic causing turbulence and further dilution of the odour. Housing also provided resistance to the spread of the odour. Odour did travel deep into the estate along a valley formed by a tributary drain that had an outlet within the PFA.

Distance of Travel

"Puffs" that were definitely confirmed as pig odours were reported as far as 900 m from the nearest pig farm source.

Direction of Travel

No matter what the direction or intensity of the prevailing daytime winds, in the early evening, there was a very light air current from the northeast toward the northwest. This current was probably due to the relative rates of cooling of land and sea and it transported odours from the pig farms into the residential estate.

Effect of Rain

The combination of high temperature and high relative humidity after a rain produced conditions for strong odour transport. However, strong smell did not invariably appear after a rain.

Other Odours

There were other malodour sources, such as sewage-treatment plants and garbage bins; however, over the period monitored, their effect was minimal and local.

Odour Tolerance

The relatively irregular appearance of strong pig odour in the residential estate and the fact that the residents were not associated with agricultural enterprises made it unlikely that the residents would adapt to pig odour as a normal part of the environment. In 1978, therefore, the Government of Singapore decided to cease further development of the site as a PFA and to phase out all the pig farms after compensating the farmers for their investment.

Questions and Answers

Odour Measurement

Question 1. Using cotton flannel cloth, fresh waste and pig odours from the production surfaces were identified as the primary nuisance. Cesspit emissions might contain more fixed gases than fresh wastes. Is it possible that these inert gases might not have the same affinity for the cloth as the gases emitted from fresh excreta? Also, would the gases from the excreta cling to the flannel longer than fixed gases? Have any tests with pure gases been made to clarify this? Would capturing the odorous gases with vacuum flasks or bags give the same results as the flannel cloth swatches?

Answer 1. Whether all gases are held with the same affinity by cotton flannel is not known. The primary basis for using this technique has been success in having people identify where the fabric has been hung.

For example, in another experiment, fabric swatches were hung in poultry, dairy, and pig houses for about 2 h, sealed in plastic bags, and transported some 800 km. The following morning, testers knew precisely where the odour had come from. This suggests that cotton is a reasonably reliable odour-storage device. It cannot be ascertained whether fixed gases were collected on the fabric or only organic gases, but if one accepts the fact that fixed gases make only a limited contribution to the odour, their affinity is perhaps not critical.

This question also deals with capturing samples of odorous air in bags and transporting them back to the laboratory for analysis. This process has some serious limitations. First, it is difficult to capture these gases in a container and to halt any further chemical reaction that might be in progress. Second, there is the problem of handling the gas after it is captured and making the appropriate dilution to present the sample to a panel. The equipment available at reasonable cost for this kind of gas analysis is inadequate. Certain universities use the technique, but none practices it on a routine basis with pig wastes.

Question 2. What are good odour-monitoring instruments? Is portable gas chromatography equipment, fitted with prepacked columns for specific odorous gases (ammonia, hydrogen sulfide), available for field studies in a PFA?

Answer 2. The scentometer, under appropriate conditions, is a very helpful instrument. For most animal waste odours, however, it is very difficult to use because the odours are only perceived during low wind velocity and generally are present in variable amounts. Under these conditions, it is very difficult to maintain a threshold number.

Chemical techniques can also be used in odour surveys. When dealing with a single odour source (e.g., a single feedlot or pig farm), the evolution rate of a gas that is uniformly produced in proportion to the amount of odour can be used as indicator. When dealing with a variety of odour sources, such as those present at the Jalan Kayu PFA, these techniques are not adequate; for example, the hydrogen sulfide survey sometimes showed the highest H_2S values in areas in which the odour was least noticeable. Therefore, H_2S cannot always be trusted as a PFA malodour index gas. The same thing can be said for a portable gas chromatograph designed to measure gas composition at even lower concentrations than lead acetate strips.

Question 3. There are some conflicting data on the minimum detectable odour levels for ammonia and hydrogen sulfide. Based on all these surveys and studies, what is the usefulness of NH_3 and H_2S measurements in an odour-monitoring program? At what levels are ammonia gases odorous?

Answer 3. The minimum detectable levels of ammonia and hydrogen sulphide have been measured by researchers when only ammonia and hydrogen sulphide were present. Because that is not the case with pig farm odours, data on minimum detectable odour can be misleading.

According to some reports, the minimum detectable level for ammonia is 47 ppm. Others claim the level to be 5 ppm or even less. It definitely is not 47 ppm, because such levels are rarely, if ever, reached in open livestock buildings and one can smell ammonia in such buildings most of the time. Of course, it is possible that the ammonia odour one senses is not entirely due to ammonia. It could be from one of the amines whose smell is much like ammonia. Moreover, the ammonia odour may be enhanced by other gases that are present. The explanation matters little. What is important is that when one smells a mixture of gases, one can detect an odour even when its components are present at a much lower level than their individual threshold values.

Question 4. Can hydrogen sulfide and ammonia concentrations be used to compare odour levels around pig estates?

Answer 4. Ammonia and hydrogen sulfide concentrations are useful indicators of malodour only when a single odour source is present. For example, if one was testing a single cesspit as an odour source in an otherwise odour-free environment, then measuring NH_3 and H_2S concentrations downwind of the cesspit would, in fact, be monitoring odour levels. However, in a PFA there, are many sources of odour besides cesspits: feedmill, feed storage, drains, pen floors, the pigs themselves, and swill.

Malodour Management

Question 5. When evaluating deodorizing agents, it was found that ammonia and hydrogen sulfide levels increased with the use of the agent. Could these agents actually promote degradation of organics to their end products and thus eliminate the intermediate products such as volatile acids that are the major sources of malodours? In other words, are these agents ameliorating malodour without reducing NH_3 or H_2S levels?

Answer 5. There has been little success with commercial products designed to eliminate odours by altering the chemical pathway of degradation. The assumption in this question that measuring ammonia and hydrogen sulphide levels may not be a fair way to evaluate the success of these materials is correct.

The most appropriate way to evaluate these commercial products is to compare them with a control. The comparison should be carried out organoleptically with cotton flannel swatches or with odourmeters. It should, however, be pointed out that such evaluations should be conducted by an independent odour testing panel, but at the expense of the manufacturer.

Odour Sources

Question 6. What is the order of magnitude of the several odour sources from a PFA such as the one studied?

Answer 6. Based on odour-monitoring work with cotton fabric swatches and the surveys, the odour smelled during the evenings was predominantly from the pen floors and the pigs themselves. The second most important odour source was the cesspits. The cesspits were actively undergoing anaerobic decomposition and exposed a reasonably large surface area for the escape of odorous gases. The third odour source in order of importance was the swill cookers; the fourth was the drain and estuary. However, the order would be different depending on the time of year and the weather conditions.

The odour of the tidal flats at the upper end of the estuary was quite objectionable at the site itself. When that odour was presented to the panelists, they did not find it particularly offensive. It could be that this swampy odour was something with which panelists who had been living in the tropics were quite familiar. In the long run, the odours from the swamps where the wastewaters were being discharged would become a major source of malodour.

Question 7. On several occasions, malodours were perceived within a fairly small area or section of a street. What factors would account for such nonuniform spread of malodours?

Answer 7. The odours were spread very uniformly and in a laminar fashion in the direction of wind flow. Odours were detected when the wind velocity ranged from 0.5 to approximately 1.2 m/s. The odours were always carried in the direction of wind movement.

However, it is quite likely that in a road perpendicular to the odour movement there would be gaps caused by localized disturbances. However, there would be no gaps parallel to the direction of odour travel. This is illustrated by the iso-osmic lines in Fig. 6.2.

Question 8. There is a strong odour from the pigs themselves. How can this be controlled?

Answer 8. Because pigs do not perspire, a clean pig has very little odour. Thus, it is not the pigs, but the feces and urine on their bodies that smell. I have seen pig farms in which the pigs were kept clean and have noted that there is no pig odour in such farm buildings.

Question 9. After a cesspit fills with settleable solids, is there much degradation and septicity at the bottom of the tank?

Answer 9. Once a cesspit is full of settleable solids, only limited degradation occurs, particularly after the pH falls to a low level. Measurements in a series of cesspits, however, indicated that pH was between 6.5 and 7. At that pH level, there should be no interference with biodegradation. Observations of several cesspits, suggest that active anaerobic decomposition was occurring.

Malodour Abatement

Question 10. How much of the odour problem in the farm area is attributed to the cesspits, and how would a system in which fresh wastes were flushed directly into the drains for central treatment compare with the present system as far as odours are concerned?

Answer 10. The initial hypothesis was that the cesspits were the primary source of odour. After organoleptic surveys on the farms and monitoring of the residential areas, it was concluded that the pig houses were the major cause of the odour, and that this odour was perceived downwind with greater intensity than cesspit odours.

In investigations with volunteer panelists, panel members did not have a strong preference for fresh manure over manure that was 1 day or more old. This would lead one to believe that bypassing the cesspits would not have a major impact on the odour from the drains. Therefore, there would be no change in the level or frequency of complaints about odours. Pollution and accumulation of sludges in the drains would be another issue.

There was sufficient evidence that the major source of odour that was causing complaints by residents was arising from the buildings and the animals. This odour was attributable to manure on the floors, on the animals, and left in the gutter after the pens were cleaned. One basis for reaching this conclusion was the extensive area involved in this particular form of odour generation, more than 100 times as much as in cesspits. Thus, for the cesspits to be an equal source of odour, they would have to be generating odorous materials at 100 times the rate. Perhaps cesspits contributed 10–30% of the total odour, whereas the buildings and animals were responsible for 60–80%. The next most important odour source was swill cooking.

Based upon tours of the area and analysis of the sources of odours, it seemed that flushing waste directly from the pig building into the drain would not appreciably influence the odour level. In the long range, however, any estuary would have an influence on odour levels. For this reason, direct flushing to a drain and provision of central treatment could eliminate a potential future problem. The other solution is, of course, to provide adequate treatment on the farm to prevent the escape of solids to the drain and, hence, to the estuary.

Question 11. Odour complaints appear to be limited to pig barns close to the housing estate. Would a wider and more pervasive odour problem develop from the discharge of untreated wastes to the estuary?

Answer 11. Yes, particularly during low rainfall periods. In the absence of wash-out rains, there would be less movement of solids and they would accumulate in the drains and turn into foul-smelling sludges. If a single challenge to pig production were to be identified, it would be to find an economically attractive and environmentally sound use for the solids. Until that can be handled, there will continue to be issues that are difficult to resolve.

Question 12. Poor building design and inadequate pig management contribute to malodour problems. Are there any instances of defects in these two factors and what would be suitable remedies or improvements?

Answer 12. The most common inadequacy was lack of slope on manure drains from the sides of the buildings to the cesspits, causing manure solids to be retained for a long period and to undergo anaerobic decomposition. This is an example of a farmer not having adequate information, because sloped gutters are no more difficult or expensive to construct than the gutters that are creating the problems.

Masking Odours

Question 13. Given that two or three farms were considered to cause much of the immediate problem, would a spray barrier be an effective temporary control measure on evenings during which favourable conditions for odour travel might emerge? If so, are oxidizing agents or masking agents the best chemicals to use?

Answer 13. No spray barriers are currently being used for the control of pig house odours anywhere in the world. A spray barrier could be used on an experimental basis to learn something about and their effectiveness for controlling pig manure odours. Unfortunately, such barriers are rather expensive and their operating results are not known. If the Jalan Kayu PFA were to be expanded, spray barriers might be required.

In terms of materials to add to the spray water, clean water that was fully saturated with dissolved oxygen would be most effective. Beyond that, masking agents, or oxidizing agents could be used in very small spray systems. One would have to be fearful of the impact of oxidizing agents in a large area, particularly their influence upon local vegetation.

Question 14. Odour-control compounds (Pit Stop, a seaweed extract, and Subdu, a mixture of bacteria and enzymes) were tested on pig waste. Ammonia and hydrogen sulfide were used as indicators of odour. The experiment was carried out for 8 weeks and both NH_3 and H_2S were constantly higher than the control levels. What is the significance? Should odour be measured using some other parameters?

Answer 14. There are many odour-control chemicals that claim to be masking agents, enzyme additives, or deodorants. Such products always contain some additional exotic materials that account for the product's effectiveness. These products have not proven particularly effective in the control of pig house odours. More important [illegible] of these materials are of such a composition that they cannot be effective. For example, those that promise to add a small amount of enzyme to the manure pit have little chance of being successful because of the massive quantity of enzyme already present.

Before any deodorant is purchased, various testing programs should be conducted. Such testing programs should be funded by the manufacturer or distributor who have the greatest potential for gain if the product is successful. As was already stated, ammonia and hydrogen sulfide concentrations are not appropriate measures of the effectiveness of these products.

A test program could be set using plastic-lined barrels containing pig wastewaters (or whatever part of the waste system is to be treated by the additive). Eight barrels should be filled approximately one-third full of the waste. Two barrels should be used as a control; two barrels should receive the chemicals at the recommended level; two barrels the chemical at one-half the recommended level; and two barrels the chemical at four times the recommended level. Cotton flannel swatches should be hung over the various barrels and an odour testing panel used to determine whether the chemicals are having any impact. Another alternative would be to use a scentometer to measure the odour intensity over the various barrels. As supporting data, NH_3 and H_2S evolution rates could be measured to understand the action of the products better.

Role of Education

Question 15. Could the odour problem be resolved by education? If the pig odour is an esthetic problem rather than a health hazard, could the residents be educated to coexist with the livestock enterprise?

Answer 15. Whenever an odour problem exists, it is appropriate and prudent to conduct an extensive education program to alleviate any fears that may exist on the part of local residents. Residents should be assured that pig odours present no danger to their physical well-being. They should also be made aware of government efforts to minimize odours if such efforts that can be visibly demonstrated. Frequently, people will be greatly relieved if they know that someone else is taking the problem seriously and that an effort is being made to minimize it. There are major benefits from an effective education program.

On the other hand, the pig odour problem does, in fact, require a technical solution. Odours are indeed an esthetic problem rather than a health hazard. However, people have now assumed the right to have their esthetic environment protected just as they have fought to have their security or health environment protected.

Role of Feed Formulation

Question 16. How effective is dietary control on pig waste odour production? Within the limits of nutrition, is it worthwhile to conduct investigations with feed additives?

Answer 16. This is definitely an intriguing approach to the problem. Some people say "we smell of what we eat." The odour of fresh manure can be rather easily altered. For example, a few drops of peppermint oil added to the feed of a number of cattle was carried quickly through the system and produced a manure with a very strong peppermint aroma. Unquestionably, this odour was quickly neutralized and as the manure underwent anaerobic decomposition the usual smell returned. In other experiments, sagebrush oil was added to diets and, again, claims were made of a less offensive fresh manure. Zeolites have been added to pig and poultry rations and various claims of success have been made.

There are certain difficulties in achieving a solution to the odour problem with diet additives. If the pigs' requirements for protein, energy, and other essentials are met, the composition of the manusre will be uniform. As it undergoes anaerobic decomposition, substantial quantities of odorous intermediates are released. If there were some way these malodorous intermediate products could be altered or replaced by more pleasant-smelling material, that would certainly help resolve the problem. However, any steps that make the odorous intermediate materials unavailable to anaerobic bacteria also tend to make these materials unavailable to the digestive system and, thus, decrease the effectiveness of the diet for meat production.

Odour Travel

Question 17. What factors determine the presence of odour only at certain periods of the night, and can the odour problem be alleviated by eliminating or modifying these factors?

Answer 17. Based upon the studies at the Jalan Kayu PFA, the primary factors that caused pig odours to be detected for a short period during the evening were wind direction and velocity. During the time in which the studies were carried out, wind velocity tended to decrease during the evening; during some evenings, it became essentially still. On still evenings, however, the direction of wind movement could be determined by lighting a match. With wind movements as slight as these, it is not hard to imagine that the direction could reverse rather frequently. Such action could cause the odour to be detectable for an extremely brief period. Of course, there are no practical ways to prevent this low wind velocity or to reverse wind direction.

Question 18. Malodours were often perceived between 1900 and 2200. Were these malodours being generated in the pig farms during the day and only reaching the residential areas at this time, or were the emissions continuous and was it only between 1900 and 2200 that the conditions were favourable for rapid dispersal?

Answer 18. The fact that odours were more frequently perceived between 1900 and 2200 would indicate that these were the times when wind conditions were most ideal for odour transport and also the times when people were more sensitive to invasion of their living area by pig odours. The farmers were not involved in any unusual practices during the evening hours. The farms had a continuous odour-generating surface and this surface released odours throughout the day and evening. It just happened that during the evening hours wind movement was such that it carried the material in an appropriate concentration to the neighbouring area.

Effects of Malodours

Question 19. Why is there no health hazard from the odours detected in the residential areas? Are there conditions under which odours could become a health hazard to nearby residents?

Answer 19. No studies have indicated that there is any disease or physiological change caused by living or working within the odorous atmosphere of livestock production facilities. Families who work in pig houses and are exposed to pig house odours constantly do not have any abnormal health problems. Therefore, one could state confidently that no physiological damage is done to residents who live in areas penetrated by pig house odours.

Depending upon the definition one gives to "health hazards," the answer to this question might be somewhat different. For example, some people get sufficiently upset over severe pig house odours to be unable to maintain a typical lifestyle. They sometimes find they cannot eat. If the value of their property was substantially reduced, some people might lose their appetite and social graces. One could argue that this, in the extreme, would be a health effect; however, PFA odours are mainly a source of nuisance. None of the gases detected among those that were penetrating the residential area was anywhere near toxic levels.

Question 20. Is the odour problem serious? Could the situation have been exaggerated by a small but vociferous group obsessed by the perceived fall in the value of their properties?

Answer 20. The odour problem associated with pig production activities is serious. People throughout the world are becoming increasingly intolerant of environmental abuses, particularly those that influence their daily lives. Animal manure odours are not an exception and, therefore, people will bring pressure to bear to stimulate action. Unless there is a technical remedy that is consistent with pig production, this could prove disastrous. There is always the possibility that a major odour incident could occur that would suddenly attract widespread publicity and bring pressure on the industry. Nevertheless, those who complain about pig odours do typically exaggerate the situation.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Understanding olfaction processes, odour perception, and development of odour standards for livestock production and waste management.
2. Demonstration of malodour capture and identification with the cloth swatch method, odourmeters, chromatographic, and wet-chemistry techniques.
3. Extent of protection under common law and livestock zoning regulations, and laws with respect to private nuisance suits.
4. Identification, classification, and development of comparative iso-osmic lines for specific sources of malodour at a specific location.
5. Classification of pig odours by source, chemical constituents, chromatographic, and other odour signatures.

Chapter 7

Algae Biomass Recovery and Utilization

This chapter deals with the design of high-rate algae ponds, the operational problems encountered, the type of algae produced, the results of the tests, harvesting and using algae as an animal-feed protein supplement, and the economic feasibility of the system on a large pig farm. The design and operation of small experimental and full-scale prototype facilities and equipment are outlined to illustrate the development and operation of a dynamic biotechnology station.

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General Background

Pig wastewater was used as a substrate to produce algae, which were harvested and processed as a pig feed supplement. The process was demonstrated with the comprehensive facilities in Singapore to be a viable resource-recovery biotechnology. Furthermore, because the treated water was recycled to flush the pig pens, the high-rate algae ponds were integrated into a total recycle system (see Figs 1.9, 1.10, and 1.11 in Chapter 1) that was tested over several years.

Algae, although larger than bacteria, are still microscopic (5–70 μm). Algae use solar energy to synthesize cellular matter from carbon dioxide, ammonia, nitrogen, and other essential nutrients in wastewater ponds. Bacteria break down the wastewater organics and release carbon dioxide, which is consumed during the day by algae that release oxygen during the day. The dissolved oxygen promotes the growth of aerobic bacteria. This symbiotic process is accelerated in high-rate ponds by mechanical mixing, which brings the organic material into constant contact with the bacteria and algae, exposes more of the algae to sunlight, and maintains the solids in suspension. Thus, in high-rate algae ponds, the organic loading rates can be much higher than in standard wastewater oxidation ponds.

The first field studies on the cultivation of algae using high-rate ponds with sewage were conducted in California in the 1950s. The concept has been studied at many research institutions throughout the world since then. In 1976, when plans were being formulated for comprehensive field studies on the recovery of algae from pig wastewaters in Singapore, there were on-going projects on algae in several countries. Field projects were visited and reviewed in Germany, India, Israel, the Philippines, Thailand, and the United States. Another comprehensive research effort had just been completed in Australia to develop algae harvesting from sewage high-rate algae ponds using continuous mechanical filtering equipment.

As extensive and comprehensive as these projects were, none of these countries experimented on a large scale with pig wastewaters. All of them had significantly different climatic conditions that made it impossible to apply directly their field studies in another country or area. Before a field project in Singapore was undertaken, these countries were visited and a series of small ponds was built to develop basic design parameters.

The full advantage of high-rate ponds could be achieved only if the algae were harvested and used. Unless harvested, the algae would settle, decompose, and thus reload the system. The widespread application of high-rate algae ponds as a dilute-wastewater treatment was limited by the economic and technical limitation of harvesting mechanisms.

Thus, one of the major thrusts of the algae project in Singapore was to develop and test algae-harvesting systems. Another emphasis was to use the algae as feed and recycle the treated water. No such system had been built or tested on a field scale anywhere.

Test Ponds

Size

Ponds built during the 10 years of study included 5-m^2 "micro-ponds," 10-m^2 "mini-ponds," 125-m^2 "pilot ponds," and 1 250-m^2 "demonstration ponds." The size of high-rate algae ponds is determined by organic loading rate (OLR), hydraulic detention time (HDT), liquid depth, and properties of the influent. Once depth is established, OLR is expressed in terms of the weight of the organic parameter (TVS, BOD, etc.) per unit surface area. This makes pond sizing a matter of simple arithmetic.

Depth

Depth depends on the degree of light penetration, which becomes limited as algae grow and add colour to the liquid. Liquid depth is normally 20–40 cm, which is much less than the 1.5–2 m depth of sewage-stabilization ponds. Normally, 40-cm side walls permit operations at lower liquid depths. However, excess height shades part of the liquid surface and thus affects photosynthesis. For general application, a depth of 30 cm is appropriate.

Organic Loading Rate

The organic loading rate (OLR) is expressed as weight of an organic matter parameter per surface unit of pond liquid. In the case of algae ponds, the daily OLR is expressed as kilograms BOD per hectare. The usual daily OLR ranges from 100 to 400 kg BOD/ha.

If the depth is fixed at 30 cm, then the daily OLR of 100–400 kg BOD/ha can be converted to a volumetric rate by expressing hectares in square metres and kilograms in grams. Daily OLR can then be expressed in terms of BOD: 33–132 g/m^3 (or mg/L). This conversion allows quick mental calculation of the dilution and concentration needed for a particular wastewater used as a substrate in high-rate algae ponds.

Hydraulic Detention Time

Hydraulic detention time (HDT) is expressed as days required for the volume of the influent to pass through the pond. It is determined by experimental trials and is affected by the time it takes for the algae to regenerate and bloom. Algae are capable of replicating within 1 or 2 days.

In practical terms, HDT should range from 2 to 10 days, depending on the mean daily flow. Low HDT is not recommended for wastewater ponds because of nonuniform flows. The peak flow can be 2 to 6 times higher than the mean, which would reduce the HDT to a few hours and wash out the algae. In ponds that use artificial media as the substrate to grow pure cultures of algae and carefully control the inflow, an HDT of 1 day is sufficient. Long HDTs are not feasible because of space requirements and high energy costs for mixing.

An HDT of 4–6 days is recommended. If the daily OLR is 33–133 mg BOD/L, the theoretical BOD concentration for an HDT of 5 days would be 165–667 mg/L, which is the range of BOD in domestic sewage.

Wastewater Concentration

Once the liquid depth, OLR, and HDT are established, the concentration of the design parameter in the influent is fixed. In the preceding example, the influent BOD had to be 165–667 mg/L. However, the BOD of raw pig wastewaters averages 3 000–5 000 mg BOD/L, 5 to 30 times more than required. Therefore, the wastewater had to be diluted to the design concentration. The best approach was to use sedimentation tanks to remove the settleable solids and, thus, minimize the volume of water needed for dilution.

Another alternative was to design the system to recycle the treated water and replace only what was bled off the system through evaporation (minus precipitation), leakage, and withdrawal volumes in sedimentation and harvesting processes. In tropical climates where rainfall may exceed evaporation, the volume of rainwater falling directly into the pond during the rainy season may cause severe washouts and may create conditions that favour algae predation.

Micro-Ponds

The first series of small test ponds for algae culture consisted of four 5-m^2 ponds that were operated from May through July 1977. Initially, the ponds were loaded on a draw-and-fill basis at daily rates of 80, 120, 160, and 240 kg BOD/ha. Liquid depth was 30 cm and the ponds were broom-mixed three times a day. *Chlorella* algae dominated for 3 weeks. Later, the two ponds with the higher waste loading rates developed almost pure cultures of *Scenedesmus* species. All four ponds were then loaded at 240 kg BOD/ha per day and the *Scenedesmus* species were maintained until the studies were discontinued in July. Algal cell counts made during this period were 8 000–10 000 cells/mm^3. However, daily variations were large and repeatability of counts was poor. As a result, this type of cell count was not made in later studies.

Mini-Ponds

Four ponds, each with a surface area of 10 m^2, were constructed in July 1977. They were equipped with low-velocity, paddle-wheel mixers. Two of the ponds were constructed with brick walls and concrete bottoms. The other two had corrugated asbestos walls sealed at the joints with silicone. The corrugated asbestos cost less than the brick walls and the silicone sealants provided effective watertight seals at the joints.

The *Scenedesmus* culture from the first series of micro-ponds was used to inoculate the mini-ponds. Daily OLRs were maintained at 150–300 kg BOD/ha from diluted settled wastewater (1 000–1 400 mg BOD/L) derived from 30 pigs. Liquid depth was 30 cm. Initially, the mini-ponds were broom-mixed. *Scenedesmus* rapidly established itself in these ponds. However, when the paddle-wheel mixers were run continuously, the algae became trapped in large bacterial flocs that resulted from aeration. The flocculated algae settled rapidly when the mixers were stopped. Timers were installed to allow intermittent mixing. *Scenedesmus* continued to be dominant.

Excess settleable solids accumulated in the mini-ponds after a few months, so frequent desludging of the ponds was required. Therefore, a depressed section was included in future larger ponds to provide for the settling of these solids and their removal from the pond.

In December, when cloudy days and rains dominated, liquid depths in two of the mini-ponds were reduced to 20 cm; the other two were maintained at 30 cm. The heavily loaded ponds became progressively brown, BOD in the ponds increased, pH and dissolved oxygen (DO) dropped, and *Scenedesmus* surrendered its dominance to *Chlorella*. Continuing adverse weather led to the deterioration of all the ponds. All feeding was stopped for 3 days and accumulated sludge was removed. Feeding resumed at lower levels (150 kg BOD/ha per day) for all four ponds and they stabilized with *Chlorella* species within several days. Attempts to restore *Scenedesmus* dominance by liming the ponds to a morning pH of 8.5 were not effective. The persistent wet and overcast weather apparently affected the algal flora, as had also been noted in the studies in Germany and Israel.

Pilot Ponds

Design of the four pilot ponds began in July 1977; construction started in November 1977 and was completed in March 1978. The ponds were hydraulically tested in April 1978 and steady operation was initiated in May 1978 and continued for more than 10 years.

Each of the pilot ponds was 1 m wide, 50 m long, and had a surface area of 125 m^2. Each pond consisted of a single loop (racetrack configuration) with a paddle-wheel mixer and a depressed section for the removal of settled solids. A mobile suction pump system serviced all four ponds. The ponds were constructed next to each other and had compacted clay bottoms. Sand (20 mm) and rolled, crushed rock (50 mm) were spread over the levelled and rolled clay soil to prevent scouring of the clay during mixing. The paddle-wheel section and the depressed section were concrete.

Low-cost walls were made by embedding precut, corrugated asbestos cement roofing sheets in a shallow concrete trench. The overlap on the sidewalls was sealed with a bead of silicone. The exposed height of the walls was 50 cm.

The paddle wheels were an original design. The paddles were made of light aluminum corrugated sheets and extended full depth to a curved bottom section to allow low-speed mixing without backflow (similar to a vane pump). The paddle wheels had variable speed drives.

Demonstration Ponds

The two large (1 250-m^2) demonstration ponds were designed in 1978; construction was tendered in March 1979 and was completed in July, but commissioning was delayed until the paddle wheels were installed in September 1979. The demonstration ponds incorporated the same features as the pilot ponds: the same type of paddle wheel (but much larger because the ponds were 7 m wide and 90 m long); a depressed section that was serviced by a hand-powered traveling carriage that could be placed anywhere in the entire 14-m width of both ponds to suck the settled solids; and corrugated asbestos cement walls. Piling made of asbestos cement sheets was imbedded into the ground to form a non-load-bearing baffle in the centre of each pond.

The main purpose of the demonstration ponds was twofold: to produce sufficient quantities of algae for feeding trials and to test at full capacity the harvesting equipment designed and built in 1979.

Pilot Pond Operation

Figure 7.1 shows a vertical view of the pretreatment facilities and a plan of the pilot ponds during the initial operation. Pond depth was normally maintained at 20 cm, with parallel runs of 20- and 30-cm depths during experimentation. Daily OLR (averaged over the test periods, usually about 4–8 weeks) ranged from 175 to 250 kg BOD/ha. Detention times of 4–16 days were tested. Initially, mixing was intermittent (15–30 min every 3–4 h). Continuous mixing at various speeds was instituted after predation by *Moina* became serious. Liming, to adjust the pH to favour the predominance of certain algae, was used for a limited period but was discontinued because of adverse side effects.

Sampling

Samples of diluted raw wastewater, primary treated wastewater fed to the ponds, and pond contents (with and without mixing) were collected and analyzed at least three times every week.

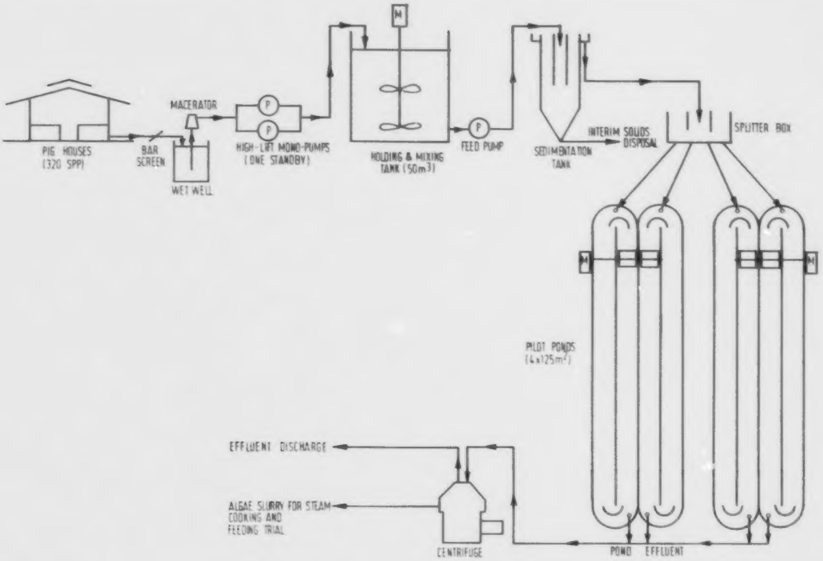
PIG HOUSES (320 SPP)
BAR SCREEN
MACERATOR
WET WELL
P
P
HIGH-LIFT MONO-PUMPS (ONE STANDBY)
M
HOLDING & MIXING TANK (50m3)
P
FEED PUMP
SEDIMENTATION TANK
INTERIM SOLIDS DISPOSAL
SPLITTER BOX
M
M
PILOT PONDS (4x125m2)
EFFLUENT DISCHARGE
ALGAE SLURRY FOR STEAM COOKING AND FEEDING TRIAL
CENTRIFUGE
POND EFFLUENT

Fig. 7.1. Pretreatment facilities and the pilot ponds. This diagram shows the flow of materials during the initial operation of the pilot ponds. Pig house wastes were macerated and then pumped (P) to holding tanks for homogenization by mixing (M). This step was necessary to get uniformity in the wastewater for the experimental feeding of the four ponds. The mixture was pumped up into sedimentation tanks to settle out solids for the biogas digester. The supernatant from the sedimentation tanks was split into four streams at the splitter box. The loading rate could be altered by varying the time of flow.

Loading

The four pilot ponds were fed daily with the overflow (settled wastewater) from the sedimentation tank (Fig. 7.1). The pond feeding started at noon and was continued for about 2 h, or as required to give the desired organic loading.

Because of variations in wastewater strength and the delay associated with BOD analysis, the operating variable used to regulate the feeding regime was feeding duration. The duration of feeding was based on preceding BOD_5 ranges, weather, and the condition of the pond as assessed by daily visual inspection of colour, the presence of predators, and the DO content.

The settled wastewater fed to the ponds was supplemented with clean make-up water that was added directly to the ponds to bring the level back to the nominal operating depth after withdrawal and feeding. The amount of withdrawal was set by the desired HDT (based on outflow), which was one of the principal variables studied. Thus, the amount of make-up water depended on rainfall and losses from evaporation and seepage.

Pond Depth

The nominal operating depth in the ponds was held at 20 cm, which gave a nominal liquid volume of 25 m^3/pond (excluding the depressed section below the pond floor). Trials with other depths were carried out in 1977 and early 1978 during the mini-pond testing, but the 20-cm depth was found to be best. At greater depths, motile algal species such as *Euglena* invaded the pond and formed a scum on its surface in the morning. This was probably because a greater percentage of the pond volume was under light-limited conditions, which would favour motile algae. These species are not desirable because they have low productivity and are difficult to harvest.

Pond Mixing

Several different mixing regimes were tried. Intermittent mixing carried out automatically every 4 h worked well. Low-speed continuous mixing caused autoflocculation during the experiments run with the mini-ponds. Mixing cycles of 3 and 4 h with 30 min of mixing were tested in the mini-ponds. The duration of mixing in the pilot pond was varied from 30 to 15 min on a 4-h cycle. No significant differences were noted among these mixing regimes. During mixing, the paddles were operated at low speed and gave an average mid-channel, mid-depth velocity of 18–20 cm/s. This velocity provided good mixing of food and kept most of the viable planktonic algal biomass in suspension, but it did not cause excessive stirring of the pond floor.

Pond Biota

Predominant Algae

The predominant organism in the ponds between June 1978 and February 1979 was the green algae *Micractinium*. *Micractinium* grew in the ponds in clusters of spherical cells, which had radial spines that extended five or more times the diameter of the individual cells. The presence of these spines gave *Micractinium* excellent retention characteristics on a paper filter or fine-weave fabric filter medium. These algae were too large to be ingested by rotifers, but were grazed by cladocerans such as *Moina* and *Daphnia*.

Algae populations were counted three times a week with a hemocytometer. Clusters of cells were counted. Total algae counts and differential counts were made using the "Thoma" hemocytometer. Differential counts were made by counting the different types of algal species until the counter registered a total of 100. The glass slip that covered the hemocytometer grid gave a depth of only 10 cm. This would not allow species larger than 10 cm, for example, *Oscillatoria* or species, such as *Micractinium*, with long spines, to enter the grid area. Therefore, if there were large numbers of *Micractinium* or *Oscillatoria* in the ponds, they would be grossly underestimated.

Another method used was the measurement of chlorophyll. Chlorophyll was extracted with absolute alcohol and the absorbance of the extract read at 665 and 649 nm against an alcohol blank. The absorbance values were measured at a wavelength of 570 nm using a spectrophotometer.

Accuracy in the determination of absorbance values depends largely on the uniformity of the particles to be counted, the cleanliness of the background solution, and the colour or turbidity of the background. Because the pond cultures were heterogeneous and the waste effluent was turbid with high background particle content, it was unlikely that the absorbance readings were representative of the algal population.

The method used for estimating chlorophyll was strictly for green algae. The pigments present in blue-green algae such as *Oscillatoria* sp. were not extracted. Also, it was extremely difficult to extract chlorophyll from *Micractinium* because of the nature of their cell walls. Several attempts were made in the laboratory to extract chlorophyll using various extraction methods (acetone, acetone plus alcohol, freezing and thawing overnight, and homogenization); however, none of these methods was successful.

Chlorophyll concentration in the ponds ranged from 3–4 mg/L to 8–12 mg/L. Weekly means over the 52-week period were around 5 mg/L. Optical density averaged below 1; total counts hovered around 10^5/mL.

Bacterial Contamination

Spirochetes, filamentous bacteria identified as *Cytophaga*, and sulfur bacteria (*Thiocapsa* and *Roscocina*) appeared during periods of depressed productivity. The sulfur bacteria infestation resulted in a pinkish supernatant; the filamentous bacteria bioflocculated the algae, especially *Oscillatoria* and *Micractinium*. Secretions from the filamentous bacteria (usually associated with bulking sludge in activated treatment systems) dissolved the thinner *Oscillatoria* cell walls and killed them. This problem had not been encountered before and had not been reported in the literature. When *Cytophaga* infected the demonstration pond, they did not do the same damage to the microflora as they did in the smaller pilot ponds.

Predators

During the early period of pilot-pond operation (up to the 25th week of initial operation) *Moina* did not appear in significant numbers. Limited rotifer infestation was observed but did not lead to any gross changes in pond biota. *Moina* began to appear intermittently and caused serious problems.

Initially, the *Moina* population was controlled by increasing the organic loading in the affected ponds to lower nighttime DO levels. This method successfully limited the extent of both rotifer and *Moina* invasions. However, on 2 December 1978, there was extremely high rainfall (over 500 mm in 24 h), which caused a large washout of algal cells and introduced a large volume of fresh water with high DO levels.

In the following weeks, the algae concentration rose steadily. However, shortly thereafter, the *Moina* population bloomed. Increased organic loading did not effectively control the *Moina* population.

Gross Biomass Productivity

Gross biomass productivity (GBP) is affected by OLR and HDT. OLR was kept constant and HDT was varied. Different HDTs were achieved by varying the volume of pond water withdrawn daily; for example, 25 mm drawn from 20-cm operating depth gave an HDT of 8 days. GBP was therefore estimated by the volume discharged multiplied by the total suspended solids (TSS) in the pond samples, and is expressed in grams of TSS per square metre of pond area per day.

Samples used to estimate productivity were collected from the ponds in the morning when the paddle wheels were turned off to simulate pond effluent during harvesting operations. Solids removed from the depressed section were excluded from the productivity calculations. The volatile suspended solids (VSS) in the pond samples averaged 91% of TSS, which indicates that TSS was a good indicator of GBP.

For the 8-day HDT, TSS in the ponds averaged 663 mg/L and GBP averaged 16.6 g/m^2 per day. A GBP of only 5.7 g/m^2 per day was achieved with 16-day HDT. It was therefore concluded that 16-day HDT was not suitable for high algal productivity. Light limitation or inhibitory effects of old cells were possible negative effects at prolonged HDT.

GBP varied by month and operating conditions for each of the pilot ponds (Table 7.1). Monthly GBP ranged from 5 to 33 g/m^2 per day. Productivity at 4-day HDT was about 30% higher than at 8-day HDT, but required the handling and processing of twice the volume of water. Hence, economic factors and other trade-offs, besides productivity, are important in the selection of optimum HDT. An HDT of 4 to 8 days is best from the standpoint of pond management. HDTs shorter than 4 days could give some improvement in yields, but at the expense of operational and possibly biological stability.

GBP also depended on the degree of predation. *Moina* consumed a significant fraction of the primary production. Adult *Moina* were excluded from the TSS determinations by straining the samples during collection. Accurate determinations of *Moina* biomass grown in the ponds were not possible because *Moina* was unevenly distributed both vertically and horizontally. Skimming the pond with a net was not a successful long-term control because juveniles and eggs passed through the net and continued the cycle.

Predator Control

Effect of Reducing HDT

When the algal population began to drop because of *Moina* infestation in February 1979, the HDT in one of the ponds was reduced to 2 days to

Table 7.1. Monthly gross biomass productivity (GBP, g/m^2 per day) and total suspended solids (TSS, mg/L) of pilot ponds A, B, C, and D in 1979.[a]

	A		B		C		D	
Month	TSS	GBP	TSS	GBP	TSS	GBP	TSS	GBP
Jan.	633	21	757	25	466	16	480	16
Feb.	467	16	221	7	333	11	258	9
Mar.	72	2	72	2	91	3	90	3
April	43	1	55	2	59	2	62	2
May	189	6	206	7	160	5	179	6
June	280	9	263	9	217	7	152	5
July	248	8	198	7	164	5	141	5
Aug.	207	7	179	6	165	6	150	5
Sept.	182	6	162	5	119	4	124	4
Oct.	105	4	189	6	79	3	182	6
Nov.	151	5	106	4	140	5	132	4
Dec.	261	9	263	9	188	6	168	6
Mean	236	8	223	7	182	6	176	6

[a] The high productivity periods in January and February coincided with domination of the algal population by *Micractinium*. Appearance of nonfilterable algae and *Moina* predators caused precipitous drops in GBP. Attempts to control *Moina* by liming and raising the pH above 9.0 resulted in changes in the algal population that took a year to moderate.

determine whether the *Moina* population could be controlled by selective washout. In theory, algae that have a doubling time of about 1 day should be able to keep ahead of the cell washout rate of 2 days HDT; however, *Moina*, with a reproduction time in excess of 2 days, should not. Although the adult *Moina* were partially removed by skimming nets, washout did not occur, and a high *Moina* population continued until the end of the test period. The algal population steadily declined to a low level (TSS about 100 mg/L) by the end of the period because of predation and dilution of substrate.

Failure to wash out the *Moina* was probably related to their nonuniform distribution in the pond and their ability to move about. For example, heavy concentrations of *Moina* were usually observed over the depressed section, which was well removed from the point of effluent discharge. Also, *Moina* eggs may have been deposited in the bottom sludge, so reproduction could take place without washout.

Effect of Liming

Lime was added to a pH of about 9.5 to try to eradicate *Moina*. This effectively eliminated the *Moina* population, but it also resulted in a shift in algal population about 1 week later from predominantly *Micractinium* to undesirable green algae that were less than 2 μm in size.

Lime addition had a pronounced effect on the turbidity of the pond as it caused sedimentation of much of the suspended and colloidal matter, as well as acting as a *Moina* biocide. Algae with rigid cell walls did not appear to be directly affected by the lime, but most of the *Euglena* (without a rigid cell wall) were lysed at the high pH.

The settled material, which dropped out after the lime addition in late February, formed a sludge blanket on the pond bottom about 3 mm thick. After a number of days, small pieces of this sludge occasionally broke free and were observed floating on the pond surface. The pieces were chalky green on top and black underneath, indicating anaerobic decomposition.

Predator Management

When the colouration of the pond changed from the usual slightly brownish green to a brilliant jade green, it was unclear whether the cause was chlorophyll extraction due to lime addition or a new organism, because routine algal cell counts dropped to near zero. Microscopic examination at high magnification (oil immersion) revealed a coccoid or slightly rod-shaped organism, a blue-green algae, that had not been previously encountered. The organism readily passed through a Whatman No. 1 filter. The blue-green algae were competing to the near exclusion of the more desirable species and were unlikely to be displaced without drastic action. The ponds were fully drained, cleaned, and restarted 2 weeks later by gradually refilling them with wastes and fresh water, but without inoculation from an outside source. However, the blue-green algae quickly reestablished themselves as the dominant species. High doses of chemical grade lime before and during start-up in one of the ponds was used because it was hypothesized that lime dosing would favour larger species that competed with *Chlorella*.

Two months of intensive experimentation with various levels of lime indicated that raising the pH above 9.0 eliminated the algae predator *Moina*, but it did not help restore the predominance of large algae such as *Micractinium*. Actually, other predators (rotifers) emerged that grazed on the small blue-green algae but could not affect *Oocystis* and other large algae. Therefore, liming was discontinued and the infected ponds were inoculated with rotifers. After 1 week of grazing on the blue-green algae, the rotifer population returned to normal levels and the larger algae began to emerge. *Moina* infestation returned 1 month later.

It was concluded from these trials that it was not possible to control predators and restore the population of *Micractinium*, *Scenedesmus*, or other large filterable algae by raising the pH with liming. In November 1979, experiments were carried out to remove *Moina* from the ponds with nets and to change the mixing pattern.

Effect of Nets

Nets (250 mesh) were installed in each pond and hand-operated fine nets were used to collect *Moina*, mosquito larvae, large rotifers (*Asplanchnopus*), and other floating solids such as leaves and grass that interfered with optimal growth of algae. The captured masses were sieved through other finer nets to isolate *Moina*. The procedure took about 10 min. During 10 days, 13.4 kg of *Moina* (5% dry weight) were collected. However, the nets were not effective in controlling *Moina* infestation because small young organisms and *Moina* cysts passed through. Also, the nets clogged quickly and required daily cleaning.

Effect of Continuous Mixing

In the course of the trials to control predators, it was found that there was less *Moina* infestation in ponds that were agitated continuously. Studies were therefore made to evaluate the effect of mixing on the *Moina* population. Two pilot ponds were agitated continuously, resulting in a reduction of *Moina*. After several days of this treatment, the predators disappeared completely. With continuous agitation of these ponds, no *Moina* infestation was observed.

For comparative studies on algal growth and yield, the other two ponds were agitated for 15 min every 4 h. In these ponds, *Moina* were present in a constant number that could not be decreased markedly by the netting operations. To test the effect of mixing on *Moina* infestation, the ponds were agitated continuously. A drastic reduction in the number of *Moina* occurred immediately, and within a few days, no *Moina* could be seen.

A possible explanation of this effect is that the predators died from oxygen deficiency, especially during the night. Even during intermittent mixing, the oxygen concentration in the ponds dropped to below 1 ppm during the night, which meant that the *Moina* had to come to the surface of the pond to obtain sufficient oxygen. *Moina* are very susceptible to oxygen deficiency. It can be assumed that, as a result of continuous mixing, the *Moina* were forced under the water surface where they remained for a certain time because of partial laminar flow in the pond and subsequently died.

Rotifers, either as small *Brachionus* or large *Asplanchonopus*, were present for only a very short time. *Brachionus* appeared mainly at the same time as a species of a very small nonfilterable coccoid algae. Both disappeared at nearly the same time. It is quite likely that the rotifers were grazing on the blue-green algae because the other green algal forms were too large for the rotifer.

Energy Consumption

Moina predation was completely eliminated when continuous mixing was introduced at the end of 1979 and continued in 1980 when more experiments were carried out on the cost of different mixing regimes. Continuous mixing controlled predators but consumed energy at an hourly rate of 1.12 W/m^2 pond surface. The power consumption of ponds with intermittent mixing was 30% less than those with continuous mixing.

Assessment of Pond Performance

After 1981, the four pilot ponds and the demonstration ponds were operated as part of a total recycle system. However, collection of data on the routine operation of each pond was continued, along with the data on special experiments conducted over the years.

The demonstration ponds were operated on a variable HDT because of the large volumes of water needed to dilute the waste to the desirable concentrations. Daily OLRs were slightly higher than in the pilot ponds and ranged from 200 to over 900 kg/ha for a few weeks at a time; the average was 350 kg/ha. Continuous mixing was practiced in the demonstration ponds.

The operating depth was maintained between 25 and 35 cm. The demonstration ponds showed greater resistance to changes in weather than the pilot ponds. These ponds also had a buffer capacity that allowed them to resist drastic changes in microflora ecology.

The settled sludge was removed from the depressed sections of the pilot ponds once a week taking about 30 min; desludging of the demonstration ponds was carried out intermittently. Failure to provide frequent desludging in the demonstration ponds resulted in flotation of the settled solids. Apparently, gases formed when the solids accumulated and caused the sludge particles to float. These floating black flocs would break at the surface into smaller pieces and inhibit algal growth.

Based on about 10 years of high-rate algae ponds operation and experimentation, the following assessments of pond performance are presented as guidelines for evaluating high-rate ponds for the cultivation of algae.

Pond Construction

Side Walls

The construction of the high-rate pond using corrugated asbestos cement roofing sheets embedded in trenches and stabilized with concrete was a novel idea that worked. Joints of the asbestos sheets were held together with stainless steel screws and sealed with silicone. No major leakage problems were experienced from the side walls. The thin corrugations minimized shading and are recommended.

Bottom

The bottom of the ponds, except for the depressed section and the areas around the paddle wheel, were constructed from crushed rock and sand placed over in situ rolled clay soil. Minor problems with leakage were experienced, but these were taken care of in time, when accumulated sludge sealed the leaks. With this construction, it was difficult to clean the pond after it was drained because of infestation with predators or excessive solids accumulation. Over the years it became necessary to completely drain some of the ponds and let them stand dry for 2 or 3 days to kill predators or undesirable algae species. The use of crushed rock, although inexpensive, is no longer recommended.

Paddle Wheels

Variable-speed motors are required for paddle wheels because mixing needs vary with time of day and weather conditions. However, variable-speed drives require more frequent maintenance and repair than fixed-speed gear drives.

Operating Depth

Optimal pond depth was 20–30 cm. Light penetration as measured by Secchi disk was between 10 and 20 cm under direct noon sunshine. Depths below 20 cm were considered impractical for larger ponds because of problems with control of pond bottom grades during construction and with hydraulics during mixing. Greater depths produced thinner cultures, and, other things being equal, caused somewhat higher harvesting costs. Deeper ponds also required stronger walls. Greater depths should be accommodated following heavy rain to prevent washout of cells. The pond design should allow freeboard and the operating level should be drawn down gradually. Excess harvesting capacity should also be provided.

There were no significant changes in productivity with depth variations. However, greater operating depths made the ponds more susceptible to periods of stress (probably because of decreased light penetration), especially at high OLRs.

Mixing

One of the concerns about the operation of high-rate algae ponds was the requirement for mixing. Continuous mixing controlled predators but consumed a substantial amount of power. Slow-speed mixing was very important for dispersing the feed and for preventing settling of the algae to the bottom of the pond. Settled algae lyse and eventually form malodorous sludge.

Speed of Mixing

When an intermittent mixing regime was used, the imparted liquid velocity had to be 18–20 cm/s. A lower velocity of 10–12 cm/s was recommended for continuous mixing. Paddle wheels operating in the intermediate mixing regime consumed 30% less power than those on the continuous regime. The speed of the paddle wheel affected power consumption. When operated to mix every 4 h for only 15 min, power consumption was 25% less than for continuous mixing at the same velocity (17 cm/s).

Effect on Biota

Intermittent mixing for 0.5 h every 3 h was undesirable, especially when a high percentage of the algae were *Oscillatoria* or filamentous algae. Algae settled to the bottom of the pond during the quiescent period and later decomposed. Furthermore, the filamentous algae aggregated, floated on the water surface, and blocked the sunlight. Consequently, the filamentous algae dominated over other species in the pond. Only the smaller species of algae (*Chlorella*, *Raphidium*, and *Ankistrodesmus*) remained after a certain time.

Hydraulic Detention Time

Table 7.2 summarizes data on GBP achieved with changes in hydraulic detention time (HDT). No discernible effect of HDT can be seen. Table 7.3 shows removal efficiencies of some pollution parameters in algae ponds at different HDTs. Because of relatively uniform climatic conditions throughout the year in tropical climates, seasonal variations in HDT are not necessary; in temperate areas, the winter HDT must be considerably longer than that in summer. However, the unpredictable nature of Singapore weather, where overcast rainy periods can occur on short notice at any time of the year, rules out short HDTs of 2 days. Table 7.4 gives cell counts and species of algae at different HDTs.

The strong nature of pig wastewater and the need to conserve dilution water favoured longer HDTs than in applications involving municipal sewage. Hence, the optimal HDT was considered to be 4–6 days. Higher productivities could be expected at shorter HDTs, at the expense of somewhat thinner cultures, higher costs for processing the excess water, and higher sensitivity to factors such as shock loads that caused reduced stability.

Table 7.2. Effect of hydraulic detention time (HDT, days) on gross biomass productivity (GBP, g TSS/m^2 per day).[a]

Daily OLR (g BOD/m^2)	GBP						
	HDT=16	HDT=8	HDT=6	HDT=5	HDT=4	HDT=3	HDT=2
32	—	—	15	—	—	—	—
30	—	—	—	—	30	—	—
20	—	—	—	—	15	—	—
20	—	15	—	—	20	—	—
20	—	17	—	—	24	—	—
17	6[b]	16	6[b]	—	—	—	—
7	—	—	—	3	4	6	7

[a] This table does not contain all the data but is representative of the experiments run. The numbers are rounded to reflect the fact that organic loading rate (OLR) and GBP are estimates and not controlled parameters.

[b] Reflects unhealthy situations in the ponds as a result of predator infestation.

Table 7.3. Removal efficiencies (% removal) of some pollution parameters in algae ponds at different hydraulic detention times (HDT, days).

Pollution parameter[a]	Removal efficiency			
	HDT=5	HDT=4	HDT=3	HDT=2
BOD_5	78.9	71.8	68.1	51.7
COD	78.4	54.5	47.2	27.4
TKN	67.8	47.5	69.0	53.6
TAN	89.6	86.0	90.0	80.6

[a] See list of Acronyms and Abbreviations for definitions.

Table 7.4. Algae count (cell units/mL) and dominant species at different hydraulic detention times (HDT).

HDT (days)	Algae count	Dominant species		
		1st	2nd	3rd
5	2.5×10^5	*Chlorella*	*Scenedesmus*	*Ankistrodesmus*
4	5.9×10^5	*Agmenellum*	*Scenedesmus*	*Chlorella*
3	12.8×10^5	*Chlorella*	*Scenedesmus*	—
2	13.7×10^5	*Scenedesmus*	*Chlorella*	—

Organic Loading Rate

Daily feeding time varied between 1 and 5 h. Normally, feeding began in the early hours of the morning (0700) and continued until noon. The volume of settled waste was supplemented with fresh water to make up for the difference between the daily drawdown and the feed volume. When the total recycling system became operational in 1982, the need for such make up waste was reduced.

Organic loading rates (OLRs) during the initial phase of the project were maintained between 175 and 250 kg BOD/ha per day. However, it was soon realized that the ponds in Singapore could sustain a much higher OLR. The ponds were able to take high daily shock loads of up to 800 kg BOD/ha over very short periods. However, during extended periods of cloudy weather, the high loads caused the ponds to deteriorate immediately. The recovery period was sometimes very long and required that the pond be drained and restarted.

Under normal operating conditions, the ponds could handle between 200 and 400 kg BOD/ha per day. The high loads were for the dry, sunny periods of the year.

Attempts were made to determine the effect of loading on species dominance. It was thought that higher OLRs favoured the fast-growing algae, *Chlorella*. However, *Chlorella* dominance seemed to occur mostly during the rainy months. The pond was extremely susceptible to "crashing" during this time of the year. *Micractinium* dominance appeared to occur with relatively high OLR and favourable weather conditions. Other smaller species, such as *Ankistrodesmus* and *Raphidium*, were favoured by lower OLRs. These observations could not be substantiated in duplicate experiments because of the inability to control and isolate the effects of other parameters. Therefore, the relation of species dominance to factors like pond depth, mixing, and OLR could not always be predicted.

OLR and method of feeding were the most critical parameters in operating the high-rate ponds. Because the characteristics of the influent wastewaters and the weather could not be controlled, the pond operator had to use judgement to vary the OLR according to the projected weather for the day. The operator could vary the OLR by varying the liquid depth in the pond. Moreover, the operator had to judge the condition of the pond to determine whether it could take a high load. Pond husbandry required that the pond be monitored daily. A computerized operation that could correlate all these factors before pond feeding would be the best way to manage high-rate algae ponds.

Monitoring Parameters

Dissolved oxygen (DO) and pH were probably the two most important parameters as far as the general status of the pond was concerned. Sudden unusual changes in DO or pH usually indicated shifts in algal culture and impending massive algal die-off.

Dissolved Oxygen

In a healthy high-rate pond, DO began to rise around 0800 and reached 14–18 mg/L within 1 h. It returned to below 0.5 mg/L at 1800 when the sun began to set and long shadows extended over the pond. The DO remained near zero from 1800 to 0700. The DO level in the pond was sensitive to sunshine and responded almost immediately to any shading by cloud cover. DO was also a good indicator of the state of health of the pond. A pond was bound to "crash" when the DO fell to 4 mg/L.

pH

Time of day and the state of the pond caused pH to vary from 6.5 to 8. Attempts to encourage the growth of *Micractinium*, *Scenedesmus*, and other species by raising the pH were unsuccessful. High pH as a result of liming caused disruptions to algal populations. However, in pure cultures, pH did dictate the growth of certain species, particularly *Spirulina*.

Appearance

The colour of the pond indicated its condition and the type of algae that were thriving. This correlation could be developed through experience and microscopic examinations. Different species had characteristic green colours; changes in colour signaled impending problems.

Control of Excess Solids

Removal of excess settleable solids was necessary. At the heavy OLRs desirable for maximum productivity and mixing velocities too low to suspend the larger bacterial floc and other heavy material, bottom deposits accumulated and caused problems within a matter of days or weeks. Anaerobic conditions at night, particularly after sudden weather shifts, may have caused the sludge to rise or otherwise resulted in the breakdown of pond performance.

The depressed section and provisions for removal by suction of settled solids were beneficial both for controlling the build-up of sludge in the pond and for periodic cleaning of the pond. The depressed section had to be desludged at least twice per week.

Productivity

High productivity levels of up to 40 g TSS/m^2 per day were achieved during periods of sunny weather without significant cloud cover. During the rainy season, daily GBP dropped below 10 g TSS/m^2. Hence, the design of the ponds and of the facilities for treatment and harvesting had to account for these large variations. Loading rates had to be lowered during adverse periods to maintain a constant level of treatment.

After the first 2 years of operation and experimentation, routine operation of the ponds over a full year resulted in an average GBP of 14–21 g TSS/m^2 per day. This range was used to calculate the effectiveness of the high-rate pond systems. The mean GBP was 18 g TSS/m^2 per day.

Wastewater Parameters

The loading rates (OLRs) and productivities (GBPs) were actually back-calculated after samples were taken and BOD$_5$ and TSS values were reported. This took at least 5 or 6 days.

For daily feeding, it was important that a correlation be found between BOD$_5$ and another wastewater parameter that could be measured within hours. In this way, appropriate dilutions for the fluctuating raw wastewater and the supernatant liquid after sedimentation of settleable solids (Table 7.5) could be determined. The collected wastewater was homogenized in the tanks, and samples were collected for overnight determination of TTS. The next morning, the TTS value of the raw wastewater was used to calculate the necessary dilution for the ideal OLR based on correlations between TTS and BOD$_5$ over the previous weeks of operation. Wastewater samples were taken three times a week during experimentation periods from 1978 to 1982. The pond operator had to collect sufficient data over a sufficiently long period to develop the necessary correlation of the critical

Table 7.5. Characteristics of influent and pond liquid content.[a]

Parameter[b]	Raw pig wastewater	Supernatant liquid	Pond liquid
TTS	12913 ± 4785 (11118–14707)	5270 ± 1766 (4607–5933)	799 ± 302 (678–919)
TSS	10692 ± 4636 (8953–12431)	3381 ± 1497 (2820–3942)	352 ± 206 (275–427)
VSS	7599 ± 2716 (6580–8617)	2630 ± 1159 (2195–3064)	272 ± 158 (213–330)
BOD$_5$	4034 ± 732 (3759–4308)	2689 ± 668 (2437–2938)	48 ± 34 (34–60)
COD	8554 ± 5087 (6647–10462)	4049 ± 2118 (3254–4842)	139 ± 68 (113–163)
TKN	—	570 ± 132 (520–620)	225 ± 28 (47–65)
TAN	—	372 ± 132 (322–421)	16 ± 12 (11–20)
TNN	—	—	2 ± 2 (0–3)
TPP	—	—	54 ± 18 (46–60)
GBP[c]	—	—	18 ± 10 (14–21)

[a] The statistical parameters are based on samples taken three times a week for the year 1981. Values are means ± standard deviation, with the range (99% confidence interval) in parentheses. The data for the pond liquid are averages for all four ponds (624 samples). The supernatant liquid was fed to the ponds after dilution to the desired OLR based on an average operating liquid depth of 20 cm and an HDT of 4 days. OLR varied and decreased in the middle of the year. These values are typical for the routine operations of the four pilot ponds.

[b] See list of Acronyms and Abbreviations for definitions. Units: GBP, g TSS/m^2 per day; all others, mg/L.

[c] Gross biomass productivity was calculated as follows: $\mathrm{GBP} = (\mathrm{TSS} \times D)/\mathrm{HDT} = (\mathrm{TSS} \times 0.2)/4 = 0.05\ \mathrm{TSS}$), where D is the liquid depth (m).

parameters with parameters that could be measured on the spot (such as TSS with the Imhof Cone or conductivity).

Algal Population Control

Population control measures had to be applied as soon as an undesirable organism appeared. Once an undesirable species was well established, eradication became difficult and often required draining and cleaning the pond. Therefore, multiple-pond installations, preferably three or more, are desirable so that pond transfer can be used to restore an ailing pond, in most cases in conjunction with control measures.

When severe problems required pond draining — for example, when the fast-growing blue-green algae took over — pond flushing and start-up with a high lime dosage restricted the fast-growing species and allowed desirable larger species to get started. Continuous heavy dosing with lime after the initial mixed population was established was not beneficial.

Encouragement of rotifer growth, for example, by moderate loading and transfer from other ponds, could be used to restrict or prevent takeover by undesirable nonfilterable species. Control measures to cause predominance of the most desirable filterable species were more subtle and complex than control of nonfilterable species. One reason may have been the apparent breakup, under high light intensity and relatively low OLR, of the binding material that held the colonial species together. This suggests a need to increase OLR under these conditions.

Algae Harvesting

The harvesting of algae had always been a limiting factor in the application of large-scale algae production systems. Despite great expectation based on the potential of algae as a source of protein, harvesting technology had not developed to an extent that made algae cultivation economically viable on a commercial scale. Thus, emphasis was placed on developing a continuous mechanical algae harvester and comparing it with the traditional methods of centrifuging, dissolved air flotation, and biological harvesting (natural flocculants, autoflocculation, predator harvesting) (Fig. 7.2).

Centrifuging

The centrifuge is best used to thicken algae slurry. In a centrifuge, the clarified liquid centrate moves continuously and is discharged via an outlet, while the thickened algae slurry migrates toward the bowl section and is discharged either continuously or intermittently through another porthole.

A disk centrifuge was installed mainly to concentrate the effluent from

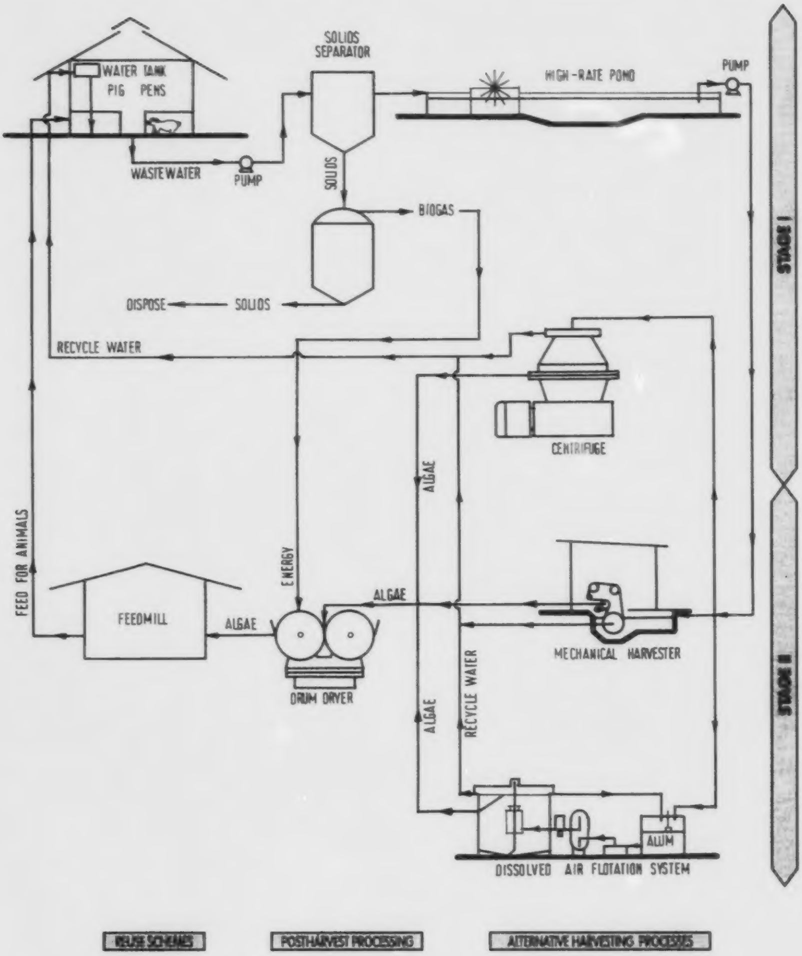
WATER TANK
PIG PENS
SOLIDS SEPARATOR
HIGH-RATE POND
PUMP
WASTEWATER
PUMP
SOLIDS
BIOGAS
DISPOSE
SOLIDS
RECYCLE WATER
CENTRIFUGE
ALGAE
FEED FOR ANIMALS
ENERGY
ALGAE
FEEDMILL
ALGAE
DRUM DRYER
MECHANICAL HARVESTER
ALGAE
RECYCLE WATER
ALUM
DISSOLVED AIR FLOTATION SYSTEM
STAGE I
STAGE II
REUSE SCHEMES
POSTHARVEST PROCESSING
ALTERNATIVE HARVESTING PROCESSES

Fig. 7.2. Flow of biomass production and recycling in algae ponds.

the high-rate algae ponds before the algae slurry was processed (Fig. 7.2). The results of trials feeding algae pond water directly into the centrifuge are given in Table 7.6.

Dissolved Air Flotation

Dissolved air flotation (DAF) is a harvesting technique that uses chemicals to flocculate solids in the wastewater stream and float them to the surface with microscopic air bubbles. A thick floating mat of solids is formed. The DAF process is used commonly to remove grease and fats in abattoirs and sewage treatment works.

Table 7.6. Algae harvested by centrifuge.[a]

Discharge interval (min)	Flow rate (m^3/min)	TSS (mg/L)		TTS (mg/L)		TKN (mg/L)		BOD_5 (mg/L)		% TKN of algae in slurry
		Influent	Centrate	Influent	Centrate	Influent	Centrate	Influent	Centrate	
30	1.85	250	40	550	300	15.94	2.90	16.50	49.80	0.50
	2.50	325	40	675	405	34.80	10.10	90.75	46.00	0.60
	3.26	200	30	650	350	31.16	8.34	163.50	101.25	0.60
	4.00	275	50	700	410	26.08	7.97	90.00	55.00	0.72
	4.42	100	20	350	300	23.18	7.25	165.00	135.00	0.36
60	1.97	200	20	550	280	21.74	2.90	180.00	59.40	0.44
	2.50	325	60	675	330	134.80	13.00	90.75	47.90	0.74
	3.00	175	40	675	370	31.88	9.01	121.50	55.50	0.83
	3.44	200	100	500	350	23.18	8.69	148.50	73.80	0.78
	4.42	100	40	600	420	20.29	10.14	192.00	141.00	0.60
90	1.95	200	43	575	270	20.05	6.52	193.50	72.30	0.73
	2.50	200	60	700	300	34.80	10.60	94.50	33.90	1.23
	3.00	200	50	700	620	34.80	28.25	96.00	87.00	1.42
	3.95	142	80	575	460	20.29	13.04	225.00	192.00	0.57

[a] Performance of the centrifuge is greatly affected by the quantity and quality of the algae in the influent. At good pond productivity, algae concentration in the slurry can be as high as 5% with liquid centrate 100 mg/L. See list of Acronyms and Abbreviations for definitions.

Often, the most difficult problem with a DAF system is the formation of air bubbles that adhere to the solid masses. Oversized bubbles do not adhere to the solids and can instead break up the flocs as they rise. To produce microscopic bubbles, a saturation tank is necessary to dissolve large quantities of air in the water at an elevated pressure. The supersaturated air–water solution must be released suddenly. The ideal location for release of the mixture is near the inlet to the DAF tank. The micro-fine bubbles then attach themselves to the solid particles and cause them to rise to the surface.

The floating mat is intermittently or slowly scraped into a collection trough. The mat must be removed slowly so as not to create excessive turbulence that would break the float.

DAF Dimensions

Based on a recycle ratio of 0.63 and a minimum HDT of 30 min, the total volume of DAF to cater to the full flow of the demonstration pond (12 m^3/h or 200 L/min) was 9.75 m^3. The unit built had a hydraulic volume of 12.2 m^3. It was 4 m long, 1.8 m wide (7.2 m^2 surface area), and 2 m deep. The hydraulic surface loading rate for the total flow of 19.5 m^3/h (12 m^3/h + 12 m^3/h × 0.63) was 2.7 m^3/m^2 per hour.

The saturation vessel was designed on a minimum 3-min HDT for 125 L/min. The volume of the tank was 375 L (0.28 m diameter, 1.4 m deep). To facilitate maximum solution of air and water, an eductor system was used. The eductor consisted of a venturi section mounted in the tank. The reduced pressure at the throat of the venturi sucked in the air and transported it to the bottom of the vertical tank where undissolved fine bubbles rose to the surface. Recycled water was used for resaturation in the pressure vessel.

The release mechanism for the supersaturated air–water in the unit was controlled by needle valves located at equal intervals in the base of the DAF tank. The recycle rate was controlled by the level in the saturator vessel. A float control mechanism regulated the level in the tank by pneumatically throttling the diaphragm valve. A centrifugal recycle pump pumped the effluent into the saturator tank. Only a small amount of air was allowed into the saturator tank.

Because the DAF was designed for experimental purposes, the inflow into the tank from the algae pond was measured before it overflowed into the flocculation chamber. A small flocculator running at very low speed (12–60 rpm) gently mixed the flocculants with the algae. The flocculant was added by means of a variable-speed metering pump.

Performance

The results of one set of experiments on the DAF are shown in Table 7.7. Before each experiment, the needle valves and nozzles were adjusted until uniform, small air bubbles were produced; the DAF tank was then filled.

For each experiment, about 5.6 m^3 of clean water was pumped into the

Table 7.7. Experimental results with dissolved air flotation (DAF).[a]

Parameter[b]	350 mg/L alum	250 mg/L alum
Influent from demonstration pond		
Feed volume (m^3/h)	6	6
pH	8.6	8.8
TTS (mg/L)	600	600
TSS (mg/L)	250	250
TKN (mg/L)	28	25
BOD_5 (mg/L)	195	169
Recycled fraction		
Volume (m^3/h)	4.8	4.8
Pressure (kPa)	365	365
Air/solids ratio	0.18	0.18
Liquid effluent		
pH	5.9	6.6
TTS (mg/L)	180	400
TSS (mg/L)	40	150
TKN (mg/L)	3	6
BOD_5 (mg/L)	23	43
Algae slurry		
TTS (%)	2.5	2.1
pH	5.3	5.8
TSS (kg/h)	1.26	0.6
Power consumption (kWh/kg)	3.02	5.92
TKN (mg/L)	1546	1546
Other data		
kg alum/kg TSS removed	1.67	2.5
Harvesting time (h)	2.5	2.2

[a] The data are typical of various runs of the DAF in 1986. The capacity of the DAF was 12 m^3/h plus another 7.5 m^3/h being recycled.

[b] See list of Acronyms and Abbreviations for definitions.

DAF to cover the needle valve. Make-up water was used for recycling. At high pressures, the recycle water became supersaturated with air; the pressure chosen for the experiment was 365 kPa. The recycle flow rate was 4.8 m^3/h and the retention time in the saturation vessel was 4.7 min.

Chemical flocculation affected the performance of the DAF. The minimum amount of alum required to produce flocs without pH adjustment was found in laboratory experiments to be 100 mg/L. Thus, alum dosages of 250 and 350 mg/L were used. Addition of alum decreased the pH. The pH of the slurry was lower than that of the effluent. Various alum dosages affected the quality of the effluent and of the slurries.

The retention time of the floating algae mat in the tank affected the solids content of the harvested slurry. If the mat was too deep, the velocity of flow pushed the bottom layers of the float out, causing a reduction in the quality of the effluent. The floating mat was too thick when harvest was intermittent. Harvesting time for the experiments was taken as the time from filling the DAF until the last scraping. The feeding time was about 2 h for each experiment.

An alum dosage of 350 mg/L produced the best effluent with the least power consumption (3 kWh/kg TSS removed) and an algae slurry concentration of 2.5% solids. Table 7.8 summarizes the experiments conducted with the centrifuge and with the DAF with the least power cost per kilogram TSS removed. The total cost of concentrating the algal slurry from 0.06 to 2.5% solids using the DAF was 0.50 USD/kg TSS removed; whereas to concentrate the algal slurry from 0.07 to 5.6% solids using the centrifuge, the cost was 0.77 USD/kg TSS.

Continuous Mechanical Belt Filtration

The use of the centrifuge to harvest the relatively dilute (0.04–0.07% TSS) pond water was inhibited by the cost of spinning large quantities of water. The DAF technique required alum to enhance solids capture. The alum had a deleterious effect on the algae produced and limited its use for

Table 7.8. Comparison of dissolved air flotation (DAF) and centrifuge for algae harvesting.[a]

	Centrifuge	DAF
Alum addition (mg/L)	—	350
Feed volume (m^3/h)	2.5	6.0
Holding time (h)	0.5	2.0
Influent (mg TSS/L)	325	250
Liquid effluent (mg TSS/L)	40	40
% removal		
TTS	40	70
TSS	88	84
TKN	71	90
BOD_5	48	88
Algae slurry/cake		
TTS (%)	5.6	2.5
kg TSS/h	0.7	1.26
kWh/kg TSS	9.6	3.02
Operating cost[b]		
Power (USD)	0.77	0.24
Alum (USD)	—	0.26
Total	0.77	0.50

[a] The comparison is based on a test run in 1986 with the same demonstration pond effluent. See list of Acronyms and Abbreviations for definitions.

[b] Power, 0.08 USD/kWh; alum, 0.15 USD/kg.

animal feed. The advantage of mechanical filters was that the harvested algae were not contaminated with chemicals.

The concept of using a filtration principle to physically separate algal cells had been tested since the early 1970s in various countries. The use of a fine-weave polyester fabric in an algae filtration harvester was first tested in Singapore. A 1.8 m diameter drum (1.02 m wide) belt filter was fabricated and put into operation in 1980.

System Design

The belt filter is shown in Fig. 7.3. The belt consisted of fine-weave polyester fabric of known mesh size. A zipper splice allowed replacement of the belt filter to suit the algal characteristics prevailing at the time. Mesh sizes ranged from 5 to 16 µm. The belt was supported on the perforated cylindrical wall of the filtration drum and the algae were deposited on the outer surface of the fabric as the flow passed radially inward. Liquid levels outside the drum were controlled by a float valve on the influent line, and a pivoting discharge pipe controlled the level inside the drum. Together, they produced the desired differential head across the fabric.

The belt left the filtration drum and passed around a 0.3 m diameter separation drum in the reverse direction. The algal solids were then on the inside of the belt in contact with the perforated drum wall. A suction box positioned within the separation drum, and sealed to the drum wall, was connected to a vacuum through a cyclone separator. The applied vacuum caused most of the algal solids to be drawn off the belt and into the suction box and cyclone, where the algal slurry was collected and periodically drawn off. The belt was then washed by water showers and returned over a series of rollers to the filtration drum.

The belt-tension roller allowed the use of a dip vat for periodic chemical or ultrasonic cleaning of the fabric, if necessary. The belt drive, which operated through the separation drum, was variable speed and allowed belt travel speeds over 10 m/min.

Operation

Pond water flowed by gravity into the main tank. The level of water in the tank was controlled by a float. The differential pressure across the belt caused the water and fine particles to flow through the cloth into the main drum. This drum was completely sealed to maintain the pressure. The belt traveled over the drum and the water flowed into the drum through the perforations. Filtered liquid accumulated in the drum and flowed out via a "gooseneck" pipe into a flow-measuring device.

A seal between the belt and the edge of the main drum was achieved with an edge-strip, which proved to be very effective. The rubber edge-strip, specifically molded for this function, was sewn and glued on both sides of the belt. The belt was joined by overlapping the ends and holding them together with a reverse-grip zipper. The main drive of the harvester was a variable-speed motor driving the smaller drum. The small, perforated

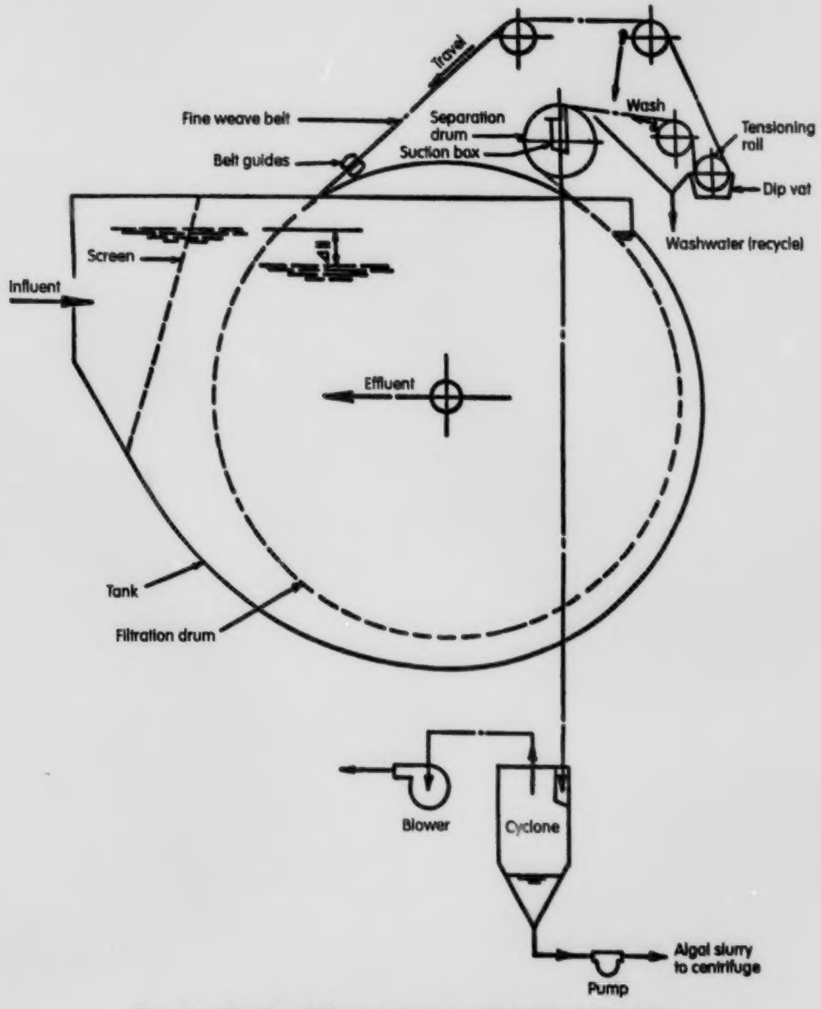
Travel
Fine weave belt
Belt guides
Separation drum
Suction box
Wash
Tensioning roll
Dip vat
Washwater (recycle)
Screen
Influent
Effluent
Tank
Filtration drum
Blower
Cyclone
Algal slurry to centrifuge
Pump

Fig. 7.3. Design of the continuous mechanical belt filter for algae harvesting.

drum rotated around a stationary suction box that sucked the deposited algal layer as it moved over the drum. Two strips of teflon seals, maintained with compressed air, provided the seal across the entire length of the suction box.

Belt tension was maintained by a series of hard, plastic, cylindrical rollers. Backwash nozzles were aligned at an angle to ensure cleaning of the belt and to reduce its "blinding" rate. A trough to allow chemical washing was included at the far end of the machine.

Two tracking mechanisms (one on each side) were located above the main drum. They consisted of two rollers that were mounted at an angle and directed the belt to its proper location.

The vacuum in the suction box was maintained by a centrifugal blower (peripheral type) that developed a vacuum of 4.0–4.7 kPa (30–35 mm Hg). The heavy slurry sucked from the belt flowed into a conical cyclone where it collected at the bottom. A pump at the base of the cyclone transferred the slurry into a large holding tank for processing.

Tests on Mechanical Harvesters

A throughput of up to 17 m^3/h at a belt speed of 22 m/min was achieved with a "reverse Dutch weave" polyester fabric with pore space in excess of 80% of its total area and 12 µm pore openings. This throughput was equivalent to about 0.84 m^3/m^2 per hour. At slower belt speeds of 5 m/min, 12 m^3/h was achieved, which corresponded to higher unit throughput of up to 2.7 m^3/m^2 per hour. A linear relationship was obtained when the results were plotted on a log-log scale (Fig. 7.4). The slurry concentration, however, was inversely proportional to the belt speed. The range varied between 1.5 and 3% TSS. Recovery was found to be independent of belt speed. A constant recovery of about 80% of incoming TSS was obtained.

Both the washing technique and the chemical used in the washing

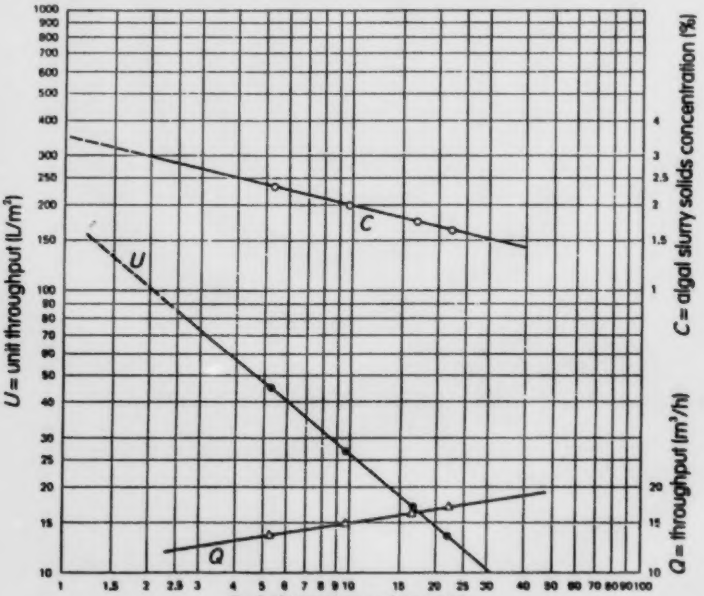

Fig. 7.4. Operational performance curves of the filter belt algae harvester: $Q = USB/60$; $U = 182S^{-0.844}$ (from data shown); and B is the belt width (0.95 m for Singapore machine; 12-µm polyester belt fabric).

process affected harvester performance. Water pressure had to be a minimum of 100 kPa (1 bar) and the nozzles had to be properly located. Acid, alkali, and sodium hypochlorite wash were tested. The hypochlorite wash most effectively overcame blinding problems.

Intermittent use of the belt also accelerated blinding. When the belts were not in use for long periods of time, dirt and bacteria settled in and blocked the pores. Extensive washing and chemicals were needed to make the belt functional again.

The differential pressure affected the flow throughput, slurry concentration, and recovery rate. At extremely low differentials below 2.5 kPa (250 mm H_2O), the flow rate was significantly lower, but when the differential was increased to 3.4 kPa (350 mm H_2O), further pressure did not increase throughput. Excessive increases in pressure resulted in high breakthrough of algal cells, especially the smaller species (0.5 µm). For *Micractinium*, a differential pressure of 3.4 kPa was sufficient to produce a thick mat of algae on the 12-µm belt. However, excessive breakthrough occurred with *Chlorella*.

The vacuum system did not improve filter belt performance. A single blower with suction capacity of about 480 m^3/h at a vacuum load of 4.8 kPa (36 mm Hg) provided the suction required. When attempts were made to increase the air flow, the slurry was sucked into the blower. During periods when *Chlorella* dominated, the use of a higher suction improved performance slightly. The side channel compressor was excellent because it was low in specific power costs and almost maintenance free.

The machine required regular greasing of the bearings and general cleaning. The sealing system, which prevented water from leaking into the main drum, could be improved. Wire wrappings should have been put on the main drum to enhance pore opening and, thus, filtration rate. The filter cloth had an economic life exceeding 500 operation-hours, even under intermittent use. After excessive chemical treatment during washing, the polyester filter belt would become brittle.

Power requirements averaged 0.3 to 0.5 kWh/m^3 of pond water treated. A 40-fold increase in slurry concentration from 0.04–0.06% solids to 1–3% solids was obtained. The use of flocculants to improve performance, especially during *Chlorella* dominance, was not successful.

The effluent discharged by the harvester had a characteristic brown colour. The BOD_5 of the effluent varied between 70 and 200 mg/L after harvesting.

The most difficult problem encountered with the filtration harvester was changes in the algal species in the pond. *Micractinium* cells, which were 12–15 µm in size and formed clusters of three or four cells with long protruding spines, were ideal. Similarly, *Oscillatoria*, *Spirulina*, and *Scenedesmus* were amenable to harvesting with the mechanical harvester.

Chlorella, *Oocystis*, *Syrecocystis*, *Ankistrodesmus*, and *Raphidium* were more difficult to harvest. They easily blinded the belt, and any excess pressure caused the cells to go through the belt. During the period of dominance of these smaller species, the throughput capacity of the machine dropped to as low as 2–3 m^3/h at a belt speed of 5 m/min. Without doubt, the algal species had a great effect on the performance of the mechanical harvester.

Biological Harvesting

Three methods of biological harvesting were tried. One method was to use chitosan, a by-product derived from shrimps and crab shells. The use of chitosan to flocculate algae had been used extensively in India. Another process was autoflocculation of pure cultures without the addition of chemicals. The third method, which manifested itself during the time the algae ponds were infested with *Moina*, was to let the *Moina* graze on the algae and then harvest the *Moina*. *Moina* are considered to be an excellent feed for tropical aquarium fish and fish fry. Aquarium fish production became a major export industry in Singapore in the 1980s.

Bioflocculation with Chitosan

Laboratory experiments were conducted to compare the flocculation effectiveness of chitosan, Zetag 63, and CF 400 (hydrolyzed polyacrylamide). Chitosan, which was provided by the Central Food Technological Research Institute (Mysore, India), was extracted from crustacean exoskeletons. It was dissolved in 1% acetic acid. Zetag 63 (cationic strength, 50%; molecular weight, $10–12 \times 10^6$; viscosity, 1 600 cP; 1% solution) and CF 400 (cationic strength, 40%; molecular weight, 3×10^6; viscosity, 600 cP; 1% solution) were dissolved in water to prepare concentrations of 5 g/L.

The conventional jar-test (1-L flasks) apparatus was used to approximate the optimum pH and polymer concentration. Algae culture samples with the appropriate reagents were mixed for 5 min and allowed to settle for 10 min. Flocculation efficiency was determined from the difference between initial and final optical densities. Optical density was measured using a spectrophotometer at 678 nm. *Chlorella* was the predominant species in the samples.

The most effective flocculants (100% removal of algae) were chitosan (20 mg/L) and Zetag 63 (5 mg/L) at an optimum pH range of 6.0–9.0 and 150–200 mg TTS/L initial biomass concentration. High pH values favoured high rate of removal of algae biomass. High polymer dosages resulted in lower removal efficiencies than those obtained at less than 20 mg/L.

Autoflocculation

Studies designed to investigate the potential of autoflocculation to harvest algae (or at least to prethicken) proved unsuccessful. Earlier reports of successful autoflocculation were carried out with pure cultures of *Scenedesmus*, not with mixtures of *Micractinium* or *Chlorella*. Attempts to repeat these in autoflocculation experiments using effluent from the high-rate ponds were abandoned after 3 months.

Moina as Algae Harvesters

Crustaceans, such as *Daphnia* and *Moina*, grazed on the algae (especially the smaller species such as *Chlorella*, *Micractinium*, and *Oocystis*) and often wiped out the entire culture. The question was whether secondary productivity (i.e., production of algae predators such as *Moina*) was greater and of more economic value than algae production, in view of the aquaculture developments that had taken place in recent years. *Moina*, a major predator in high-rate algae ponds, was an excellent food for tropical fish fry. *Moina* spp., fresh water cladocerans, were being used as food for fry and were being exported.

Moina Production Experiments

The four pilot ponds were used in experiments in 1987. The liquid depth was maintained at 30 cm and the inflow volume was controlled at 3.75 m^3/day. The working volume of each pond was 37.5 m^3 and the HDT was 10 days. The mixing paddle wheels were run continuously at a minimum speed of 0.2 m/s throughout the entire period of experimentation. The paddle wheels were stopped during discharge and to top up the ponds with water. The daily operation of the ponds consisted of sampling, discharging from the pond a volume of 3.75 m^3 (30 mm pond depth drawdown), and then feeding 3.75 m^3 of pig wastewater supernatant from the primary sedimentation tanks (see Fig 7.1).

The inoculum consisted of *Moina* spp. collected locally. The *Moina* were acclimatized in diluted pig wastewaters for 3 days using effluent from the primary sedimentation tank. The ponds were seeded with 185 mL of *Moina* inoculum 1 day after the first feeding of the pond with primary sedimentation effluent.

The ponds were emptied, cleaned, and allowed to dry for 2 days before the experimental trials were begun. Four OLRs were tested: 39, 65, 128, and 256 kg BOD/ha per day; each experimental OLR was replicated. The first trial lasted 6 days and tested the two higher OLRs; the second trial lasted 11 days and tested two lower OLRs.

Composite samples from five sampling points within each pond were collected daily for laboratory analyses. Hours of sunshine, rainfall, dissolved oxygen, and pond temperatures were measured daily.

Moina populations were measured using two methods. In one method, daily 2-L samples were taken from five sampling points in each pond. The 10 L of composite sample were filtered to obtain only *Moina* (other organisms were manually removed). The *Moina* were then rinsed into an Imhoff cone with a 40% formaldehyde solution that killed the *Moina* and caused them to settle to the bottom of the cone. The formaldehyde solution did not kill plants or larvae; therefore, the volume at the bottom of the cone was assumed to represent the *Moina* population. The volume of *Moina* that settled was recorded, and the number of species and the total count were enumerated with a hemocytometer (Newbauer) (Fig. 7.5).

The second method of measurement was used after the 6th day of cultivation. A "fine-mesh scoop net" was dragged three times over a fixed distance at the water surface. The trapped *Moina* were enumerated as wet weight per unit pond surface area (Fig. 7.6).

Samples were also observed in the field and under a compound microscope to determine the presence of other organisms, and particularly *Moina* predators such as beetles and tadpoles.

Environmental factors were quite different for the two trials. In the first trial, *Moina* were harvested on the 6th day, before reaching their maximum population; the culture period in the second trial was prolonged to 11 days. The *Moina* population reached its peak on the 7th day after feeding and then declined rapidly (Fig. 7.5). Other work reported in the literature confirms that *Moina* take 5–9 days to reach their population peak and then decline rapidly.

The *Moina* population was the smallest at a daily OLR of 39 kg BOD/ha, possibly because of insufficient nutrients. However, even with a high daily OLR of 256 kg BOD/ha and an algal bloom, a high *Moina* density could not be achieved. This could be due to the NH_3 nitrogen concentration, which reached 20 mg/L and may have been toxic to these cladocerans.

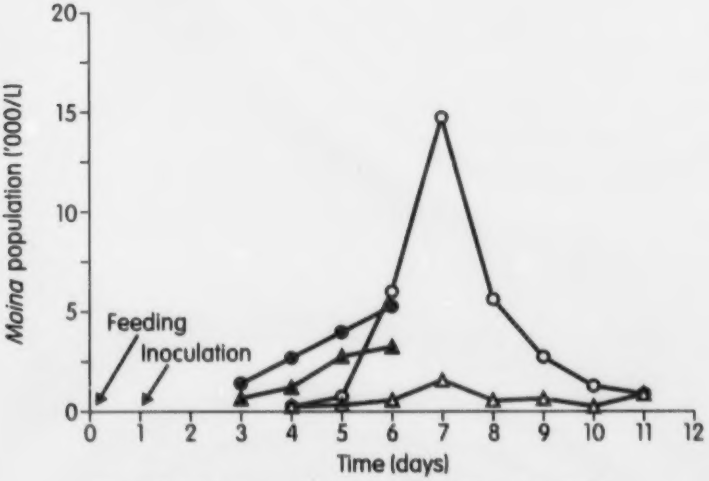

Fig. 7.5. *Moina* population as affected by daily OLR.
First trial: ▲, 128 kg BOD/ha; ●, 256 kg BOD/ha.
Second trial: △, 39 kg BOD/ha; ○, 65 kg BOD/ha.

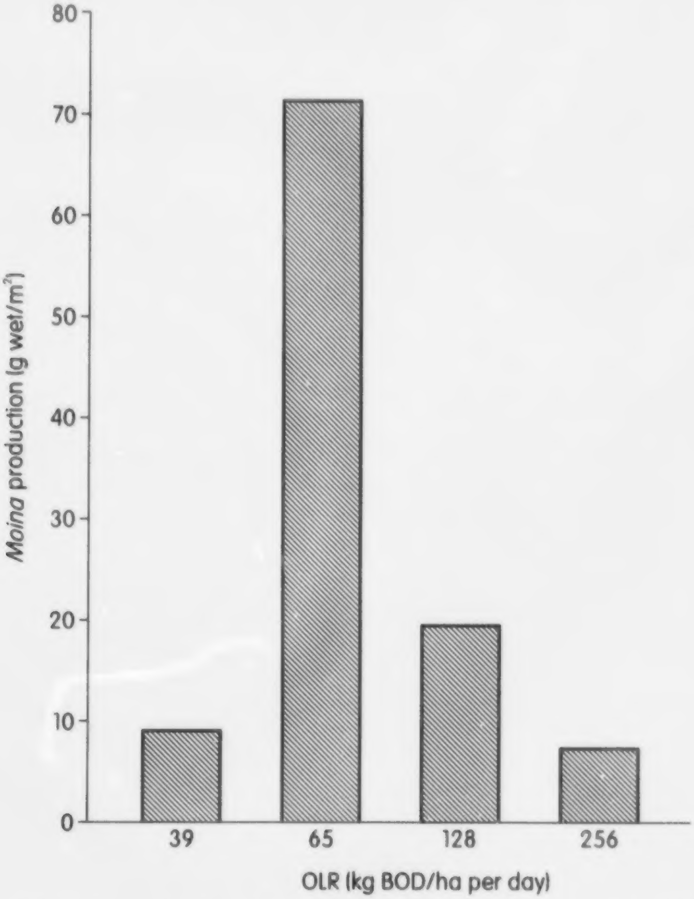

Fig. 7.6. *Moina* production after 6 days of cultivation at daily OLRs of 39, 65, 128, and 256 kg BOD/ha.

Postharvest Processing of Algae

The algae slurry produced from the continuous belt filter harvester had a dry matter content of only 1–3% TTS; from the DAF harvester, the concentration was 4–10% TTS. This wet slurry, besides being voluminous, could not be stored for long; otherwise, the algae cells would lyse and emit a rotten fishy odour. Thickening was the first step in postharvest processing. However, because the algae had thick cellulose walls that could not be digested by nonruminants, the dewatering stage included processes to rupture the algae walls and make the cellular nutrients available to animals such as pigs and chickens.

Algae Thickening

The algae slurry harvested from the high-rate algae ponds with the continuous mechanical harvester could be thickened 10-fold using disk and decanting centrifuges. Concentrations of 8–23% TTS could be obtained from a 1–2% TTS slurry. The total power requirements for harvesting and thickening ranged from 0.3 to 0.9 kWh/kg TTS of algae produced.

Solar Drying

A low-cost drier with perforated trays was built for solar drying of algae. Drying was aided by burning biogas at the bottom of the drier. Thin layers of algae were placed on the trays. The dried algae had a solids content of about 30% TTS; but the nutritive value was limited because the cell walls had not been ruptured.

Rupturing of Algal Cell Walls

The nutritive value of most of the algae grown in high-rate ponds depended on the type of postharvest processing used. With the exception of blue-green algae *Spirulina*, most algae had relatively thick cellulose-containing cell walls that made the untreated algae indigestible by nonruminants. Only ruminants possess the microorganisms that produce the gastric enzyme cellulase, which hydrolyzes the cellulose cell wall and makes the protein available and digestible without further processing. If the biomass is to be fed to pigs or chickens, the algal cells must be ruptured.

The high protein content of the algae is subject to rapid deterioration, especially under tropical conditions. Deterioration of the algae occurred within 24 h, and produced an extremely foul fishy odour. Vital proteins and amino acids were lost during the deterioration. Therefore, the algae must be used quickly or dehydrated for storage.

The cellulose cell wall can be broken in a variety of ways, including thermal shock, enzyme action, acid reaction, and mechanical means such as ultrasonic vibration. Chemical alteration of the cell walls was accomplished with butanol-induced autolysis or with agents that break hydrogen bonds, such as phenol, formic acid, or urea. The major problem with chemical treatments was the need to recover the solvent and ensure that the final product was not toxic.

Common mechanical and thermal methods of cell wall rupture are boiling, spray drying, and drum drying. Thermal shock was by far the most practical method. Instantaneous exposure to very high temperatures causes sudden expansion within the rigid walls (possibly because of vaporization). This sudden expansion stresses the wall, leading to its rupture and the release of cellular contents. Thermal shock was achieved with a drum drier, spray drier, direct cooking, or steam injection.

The project evaluated the performance of both a drum drier and a locally fabricated steam injection apparatus. The product from the drum drier was a flake that could be stored readily; the steam injection system produced a wet slurry for direct feeding. Because there were no effective ways to evaluate the digestibility of the products of the two methods, feeding trials were carried out. Drum drying, although expensive, was the most efficient process for breaking the algal cell and making the valuable protein digestible. In addition, it sterilized the final product.

Drum Drier

In the drum drier, the algal slurry was subjected to a shock temperature of up to 120°C for a short time. The high temperature caused instant vaporization of the protoplasmic water. The sudden increase in pressure ruptured the cell walls and released the cytoplasm. Attempts to view the phenomenon under the microscope were unsuccessful. The drum drier was heated with supersaturated steam to give a surface temperature of 110–120°C. When the algal slurry was sprayed on the rotating drum, it spread into a thin layer. The blades constantly scraped the dried algae flakes off the drum surface before they burned. The final moisture content of the algal flakes had to be 8% for safe storage.

Some problems were encountered with the drum drier:

- The spraying mechanism did not work as expected because the control rate could not be adjusted properly and the spray nozzle choked constantly.
- The blades needed frequent sharpening (every 20–30 h of operation) and adjustment of the blades was critical (if the algae remained on the drum too long, they burned; excessive scraping produced insufficiently dried algae that grew mouldy during storage).
- The algae had a tendency to stick to the cast iron drum surface and, although stainless steel drums would be preferable, they were very expensive (intermittently rubbing palm oil on the drum overcame this problem).
- The energy consumption of the drum drier was high, almost 10 kWh/kg of dried algae produced (10% moisture) and thermal efficiencies were below 25%.
- The operation of the drum drier was slow and labour intensive.

Steam Injection

An alternative to drum drying that was investigated was the atomizing nozzle. Steam and algal slurry were pumped into a nozzle, which is analogous to a spray-paint gun. The high-pressure steam was allowed to expand and suck in the algal slurry. During contact, algal cells were expected to rupture. The steam-cooked slurry could be used directly for feeding (wet feeding), mixed with other ingredients to form a paste, or dried in a conventional dehydrator. Rupture of the cell walls with this system could not be confirmed.

Algae Utilization

Nutrient Quality

The nutrient quality of the algae biomass could be determined by two independent test procedures: estimation based on the chemical composition of the algae or feeding trials that monitored animal response in food uptake, weight gain, physical and physiological appearance, and carcass quality. The essential parameters to be determined from chemical analysis were lipids, crude fibre, ash, and protein, although many other tests are of value in assessing the quality of the algae as a feed. The amino acid profile of the algae is most critical. Table 7.9 lists the major feed parameters of the algae biomass from the high-rate ponds.

To compare the results of feeding trials with other published studies, the protein efficiency ratio, biological value, digestibility coefficient, and net protein utilization had to be determined.

Table 7.9. Composition of pond algae biomass.[a]

Parameter[b]	Proportion
Crude protein (TKN × 6.25) (% DM)	55.5
Ether extract (% DM)	6.2
Ash (% DM)	9.9
Calcium (% DM)	2.3
Phosphorus (% DM)	1.9
Gross energy (kcal/kg)[c]	5507
Amino acids (% CP)	
Aspartic acid	5.08 (4.55–6.07)
Threonine	3.78 (3.11–4.28)
Serine	3.17 (2.50–3.57)
Glutamic acid	11.10 (10.66–11.65)
Proline	4.40 (3.97–4.78)
Glycine	3.56 (3.15–4.07)
Alanine	5.17 (4.37–6.16)
Valine	3.75 (3.17–4.51)
+Cystine	3.58 (2.44–4.47)
Methionine	0.80 (0.30–1.42)
Isoleucine	3.22 (2.31–4.22)
Leucine	6.74 (5.83–7.75)
Tyrosine	3.28 (2.40–4.34)
Phenylalanine	3.43 (3.00–3.63)
Lysine	3.80 (3.57–4.24)
Histidine	1.66 (1.30–2.12)
Arginine	3.94 (3.70–5.49)

[a] Centrifuge-harvested algae were drum-dried to 6.5% moisture flakes before they were analyzed on the automated amino acid analyzer.

[b] TKN, total Kjeldahal nitrogen; DM, dry matter; CP, crude protein. Amino acid values are means, followed by the range in parentheses.

[c] 1 cal = 4.187 J.

Lipids

Lipids are not of primary importance and fluctuate with variations in the algal strains that make up the tested biomass. Lipids are determined by ether extraction and should be analyzed with special reference to fatty acids with unusual structure. The lipid content of the algal biomass was found to be about 6.2%. The ratio of polyunsaturated to saturated fatty acids was not calculated.

Crude Fibre

Because the amount of crude fibre in a diet influences its digestibility and nutritive quality, it should be estimated.

Ash

The total amount of ash in the biomass indicates the nutritive quality of the product. The total fixed solids, which constitute the ash, amounted to 9.9%. In addition, the biomass should be analyzed for calcium (2.3%), phosphorus (1.9%), iron, alkali and alkaline earth elements, and heavy metals (with special attention to lead, cadmium, and inorganic and alkyl mercury).

Protein

Crude protein content was calculated to be 55.5% by multiplying total Kjeldahl nitrogen (TKN) by 6.25 (Table 7.9). A more appropriate estimate of protein content can be obtained using the Biuret method.

The TKN method has been used to estimate protein in animal tissues and feed products but, for microbial cells, the method is not feasible because of the large amount of nonprotein nitrogen, especially in cell walls, lipids, and nucleic acids. In spite of the accuracy of the Kjeldahl method, the determination of the protein content of microbial cells using the total nitrogen method was grossly inaccurate unless allowance was made for nonprotein nitrogen. If the total nucleic acid content, which could amount to 37% on a dry weight basis, was subtracted from 6.25 × TKN, a more reasonable approximation of crude protein was obtained. If the crude protein content of the algae biomass was overestimated by including the nonprotein nitrogen, errors were made in the feed formulations used in the animal feeding trials. This also affected the interpretation of the feed conversion ratios between the controls and the supplemented meals.

In the Biuret method, chlorophyll is extracted with ethanol, the algal cells are treated with alkali, and a 2.5% copper sulfate solution is used to produce a reddish-violet compound formed by the chelation of cupric ions. Proteins form similar copper chelates in alkaline solution. The resulting coloured solution was read at 555 nm against a water blank processed in a similar fashion. Bovine serum albumin was used as the protein standard.

Only a limited number of experiments were carried out to compare the two methods. Except for two cases, all other measurements of Biuret protein were much lower than the crude protein (TKN × 6.25) estimates. This was expected. Errors in TKN protein calculations are due to nonprotein nitrogen as well as experimental errors; errors in Biuret protein estimates are due to experimental errors during chlorophyll extraction before protein hydrolysis and loss of cell mass during the washing and centrifuging required for the process.

Amino Acid Profile

The nutritive quality of a feed is mainly determined by its amino acid composition (see Table 7.9). In Table 7.10, the average amino acid profile of algae and pond biomass are compared with the amino acid profile of chicken eggs and the recommended amino acid content of an ideal protein for human consumption.

Lysine is the principal essential amino acid likely to become bound and therefore unavailable as a result of heat treatment (Maillard reaction) during processing (drum drying or excessive boiling). Therefore, lysine determinations are critical. For additional information on the nutritive value of the algal protein, the presence of nonprotein nitrogen, derived from amides, amines, or nucleic acid, also must be determined.

Chemical analysis indicated that the nutritive quality of algal protein, based on its amino acid profile, compared well with other protein sources. As in many other proteins, the amount of sulfur-containing essential amino acids was low. This deficiency could be overcome by adding the required amount of amino acids directly, or by supplementing the algal protein with other protein sources rich in such amino acids. However, the actual feeding value could be determined only through animal feeding trials.

Table 7.10. Amino acid profile (% of total protein) of algal biomass protein.[a]

Amino acid	Ideal minimum	Chicken egg	*Scenedesmus*	*Chlorella*	Pond biomass
Isoleucine	4.0	6.29	2.01	4.5	3.22
Leucine	7.0	8.82	7.06	9.3	6.74
Lysine	5.5	6.98	4.65	5.9	3.80
Phenylalanine	6.0	5.73	3.79	4.2	3.43
Tyrosine	—	4.16	1.37	1.7	3.28
Cystine	3.5	2.43	1.29	0.7	3.58
Methionine	—	3.36	2.44	0.6	0.80
Threonine	4.0	5.12	3.22	4.9	3.78
Tryptophan	1.0	—	1.20	—	—
Valine	5.0	6.85	5.89	7.9	3.75
Proline	—	4.16	3.44	5.0	—
Alanine	—	5.92	10.98	12.2	5.17
Glutamic acid	—	12.79	8.87	10.5	11.10
Glycine	—	3.31	5.86	10.4	3.56
Aspartic acid	—	9.62	10.86	8.8	5.08
Arginine	—	6.09	5.68	5.8	3.94
Serine	—	7.65	2.93	5.2	3.17
Histidine	—	2.43	4.31	1.7	1.66

[a] The ideal minimum is based on the FAO/WHO requirements for an essential amino acid profile in human foods. The *Scenedesmus* and *Chlorella* data are for pure cultures grown on artificial media. The pond biomass data are based on four batches harvested in 1979 and drum dried to flakes with 6.3% moisture content.

Animal Feeding Experiments

Although chemical analysis gave valuable information about the nutritional value of the algae, it was no substitute for biological appraisals of protein quality using animals. Nutritional evaluations had to be made by feeding the biomass to laboratory animals and monitoring their response using internationally accepted parameters.

Protein Efficiency Ratio

The determination of the protein efficiency ratio (PER) is the most useful and simple way to estimate the nutritive quality of proteins in a short time (4 weeks). It is carried out using weanling rats.

The PERs of two types of algae harvested over two different time periods were determined. Two additional diets using casein and soybean meal as the protein sources were included for comparison.

Twenty male Wistar rats with an average initial live weight of 56 g were divided randomly into four groups of five rats each. The rats were fed ad libitum with four different diets: two containing algae of 49.4 and 53.7% crude protein (CP), one with casein, and the other with soybean meal. All diets were formulated to be isonitrogeneous with 10% CP to accentuate the differences in their protein quality.

Rats were weighed after 24 h without feed to obtain empty gut weights. Leftover feed was weighed to derive the net weight of the feed consumed. PER was calculated by dividing the gain in body weight after 28 days by the weight of CP consumed (Table 7.11).

The two types of algae used in the diets were different in their CP content (49.4 vs 53.7%) and their palatability (daily consumption, 13.5 vs 12.3 g algae/rat); however, their PER values were similar (1.71 vs 1.68). This indicated that the species of algae harvested had different physical characteristics but the same protein quality.

Table 7.11. Results of protein efficiency ration (PER) tests for algae biomass at 49.4 and 53.7% crude protein (CP) compared with casein and soybean meal.

Parameter	Algae		Casein	Soybean meal
	49.4% CP	53.7% CP		
Avg. initial body weight (g/rat)	56.0	58.6	56.5	55.2
Avg. body weight at 28 days (g/rat)	110.2	108.6	114.6	118.2
Avg. body weight gain (g/rat)	54.2*ab*	50.0*a*	58.1*ab*	63.0*b*
Feed consumed (g/rat)	376.7*b*	343.8*c*	296.6*a*	347.4*c*
CP consumed (g/rat)	40.3	37.5	29.4	35.4
PER	1.35*b*	1.33*b*	1.98*a*	1.78*a*
PER, adjusted	1.71	1.68	2.50	2.25

Note: Values followed by a different letter(s) within the same row differ significantly ($p < 0.05$).

With regard to protein quality, the algae was inferior to both the soybean meal (PER 2.25) and casein (PER 2.50). The algae protein could be lacking some of the essential amino acids as a result of the particular species of algae present or the processing conditions.

Pig Feeding Trial

A total of 18 pigs with similar genetic background and initial body weight (32 kg) were randomly divided into three groups. Each of these groups received one of the following dietary treatments:

- Standard diet: 74.5% ground maize, 5.0% rice bran, 2.5% fishmeal, 15.5% soybean meal, 1.5% mineral supplement, and 1.0% microingredients.
- Standard diet with 52% of its soybean meal replaced by steam-boiled algae.
- Standard diet with 100% of its soybean meal replaced by steam-boiled algae.

Pigs in each treatment group were fed according to the regime practiced on the farm (ad libitum).

At the end of the trial, one pig from each treatment group was randomly chosen for organoleptic, macro, and micro examinations for taste, taint, bacteriology, and parasitology after slaughter. All the pig carcasses examined were fit for human consumption. No pathological changes were found. Organoleptic tests showed that the meat was free from any abnormal taste and taint.

However, daily weight gain decreased from 0.58 kg with the standard diet to 0.54 kg for the pigs whose soybean meal component was replaced with algae at the rate of 52%. When 100% of the soybean was replaced with steam-boiled algae, daily gain decreased to 0.46 kg, which was statistically significant at the 5% level of probability.

The result of the feeding trials demonstrated that steam-boiled algae could replace 52% of the soybean meal in the diet with little reduction in growth rate or feed efficiency. However, total replacement of soybean meal resulted in significant reduction in both growth rate and feed efficiency.

Digestibility Coefficient

Six castrated male pigs weighing 36 kg each were used to determine the digestibility coefficients (DCs) of drum dried algae. The animals were each fed 1.6 kg/day of one of three pelleted feeds:

- Standard diet containing 0% drum-dried algae.
- Standard diet containing 10% drum-dried algae.
- Standard diet containing 20% drum-dried algae.

The pigs were held in individual metabolic crates that allowed separate collections of feces and urine. The collection period was 7 days and was preceded by an adjustment period of 10 days. DCs of the drum-dried algae were estimated by regression analysis. For the crude protein nitrogen of the algae biomass, DC averaged 27%, which is almost half that normally reported in the literature for algae fed to pigs. Apparently, the algae cell walls were not all ruptured.

The digestibility trial showed that the algal protein was poorly utilized, which disagrees with work published by others. DC for carbohydrate (44.2%) was, however, similar to the figure obtained by others. Both studies suggest that algae are a low-energy feed because of low carbohydrate digestibility and high ash content. The DC of the dry matter in the algal biomass was 32.6%; for the organic matter, DC was only 36.8%

Despite these shortcomings, the feeding trials established that algae could replace part of the soybean meal in a 16% CP corn–soybean pig grower diet with statistically little reduction in growth rate and feed efficiency.

Feeding Trials

The nutritive value of drum-dried algae was evaluated using 100 "day-old" TM Brown broiler chickens. These chickens were randomly divided into four groups of 25 and were fed one of four diets. The diets were formulated so that drum-dried algae replaced 0, 33, 67, and 100% of the soybean meal. The starter mash was offered up to 28 days of age; the finisher was used until the 56th day, when the chickens were slaughtered.

There was a linear effect of level of drum-dried algae on growth rate: 33, 67, and 100% replacement of soybean meal with algae resulted in 12, 21, and 30% reductions in growth rate, respectively. No differences were observed in feed efficiency and mortality rate (4%) between the control and the 33% replacement diet. However, the mortality rate jumped to 8 and 16% at the 67 and 100% rates of soybean replacement, respectively.

One reason for the different growth rates could be the hygroscopic nature of the dried algae, which inhibited normal intake by causing impacted beaks. Another possible cause of reduced intake could be its bitter taste. Lysine deficiency might also be a cause of the lower performance of the broilers.

All the broilers with diets containing algae had a dark golden pigmentation in their skin, shanks, and meat. The relation of algae content to colour intensity was not linear: broilers fed with the lowest level of algae had the highest colour intensity. No explanation can be offered for this anomaly.

The nutritive value of algae harvested chemically with the DAF and mechanically with the filter belt was evaluated again in 1980 using both broiler chickens and grower pigs. The pigs and chickens on diets containing mechanically harvested and drum-dried algae did not perform as well as the controls; however, the differences were small. Broiler chickens and grower pigs with diets containing algae harvested with chemicals using the DAF did poorly, as did chickens fed algae that was mechanically harvested but boiled instead of drum dried. The poor performance of the broiler chickens was likely due to the high aluminum content of DAF algae. A high level of aluminum in the feed is toxic and interferes with the metabolism of other minerals. Steam boiling was obviously insufficient to rupture the cell wall of the algae and, therefore, the cell contents were not available for digestion.

Postmortem Examination

At the end of the latter two studies, a proportion of the broiler chickens and grower pigs were sampled and subjected to detailed postmortem and histopathological studies. The visceral organs of the control birds (without algae) appeared to be normal throughout the whole feeding trial. Histopathological studies showed only mild fatty changes in the livers.

However, chickens with diets containing algae showed an intense yellow colouration of muscles, fat, and skin. The DAF diet produced a less intense discolouration than drum-dried algae. Both groups of birds had fatty livers and pale swollen kidneys. Histopathological studies revealed that their livers showed increased numbers of lymphocytes in the periportal tracts; the kidneys had focal interstitial nephritis and ureteritis. These findings are consistent with mycotoxicosis.

All but two pig carcasses appeared to be normal on postmortem examination. One of the pigs with a diet containing boiled algae had purpural hemorrhages in the fat and subcutaneous tissue, hemorrhagic lymph nodes, and splenic hematoma. One of the pigs in the group fed drum-dried algae had liver cirrhosis. Histopathologic examination revealed that the cirrhosis consisted mainly of eosinophile cells.

Algae Feeding Criteria

No national or international regulations or laws exist about the use of algae or other forms of single-cell protein as food or feed. Based on the recommendations of international guidelines for various feed sources, the results of the Singapore tests on algae utilization, and a review of work performed elsewhere, the criteria given in Table 7.12 are offered as guidelines for future research.

Economic Feasibility of Algae Systems

An economic feasibility study was performed on the treatment of the waste from a 30 000-SPP farm in Singapore and Malaysia using a high-rate algae pond system (Fig. 7.7) and on saving 25% of the cost of soybean meal by substituting harvested algae. In the analysis, the price of the drum-dried algae was assumed to be the same as soybean meal: 405 USD/t in 1985 and 528 USD/t in 1980. Another benefit assigned to the algae system was the price of treated water that would be recycled (the same price as potable water, 0.40 USD/m^3, from the public water network). Another

Table 7.12. Selective qualitative criteria for the assessment of algae as a source of food and feed.

Component/characteristic	Level
Crude protein (TKN × 6.25)	45%
Ash	10%
Nucleic acid	6%
Protein efficiency ratio (PER)	1.80
Biological value (BV)	75
Digestibility coefficient (DC)	75%
Net protein utilization (NPU)	56
Mercury	0.1 ppm
Lead	7 ppm
Arsenic	2 ppm
Cadmium	1 ppm

Table 7.13. Costs of systems for the production of algal biomass.

Item	Thailand (1978)	Israel (1979)	Israel (1979)	Singapore (1981)
No. of effective days/year	300	350	365	365
Size of ponds (ha)	11	10	6.7	6
Daily GBP (g/m^2)	15	21	49	17.5
Annual algal yield (t/ha)	45	74	179	64
Interest rate (%)	4.8	8.6	8.2	10
Investment capital costs ('000 USD)				
Ponds	1209	594	2350	765
Harvesting and processing	416	1540	1567	795
Other costs	938	558	121	656
Total	2563	2692	4038	2216
Annual costs/benefits ('000 USD)				
Fixed costs	148	231	332	222
Operating costs	625	535	413	272
Total cost	773	766	745	494
Benefit for treatment	—	—	400	400
Net cost	773	766	345	94
Annual cost (USD/t algae yield)				
Capital	295	312	278	577
Maintenance	436	90	61	353
Fuel and electricity	183	78	53	52
Chemical	92	317	103	—
Labour	516	133	94	304
Water	40	106	33	—
Total	1562	1036	622	1286

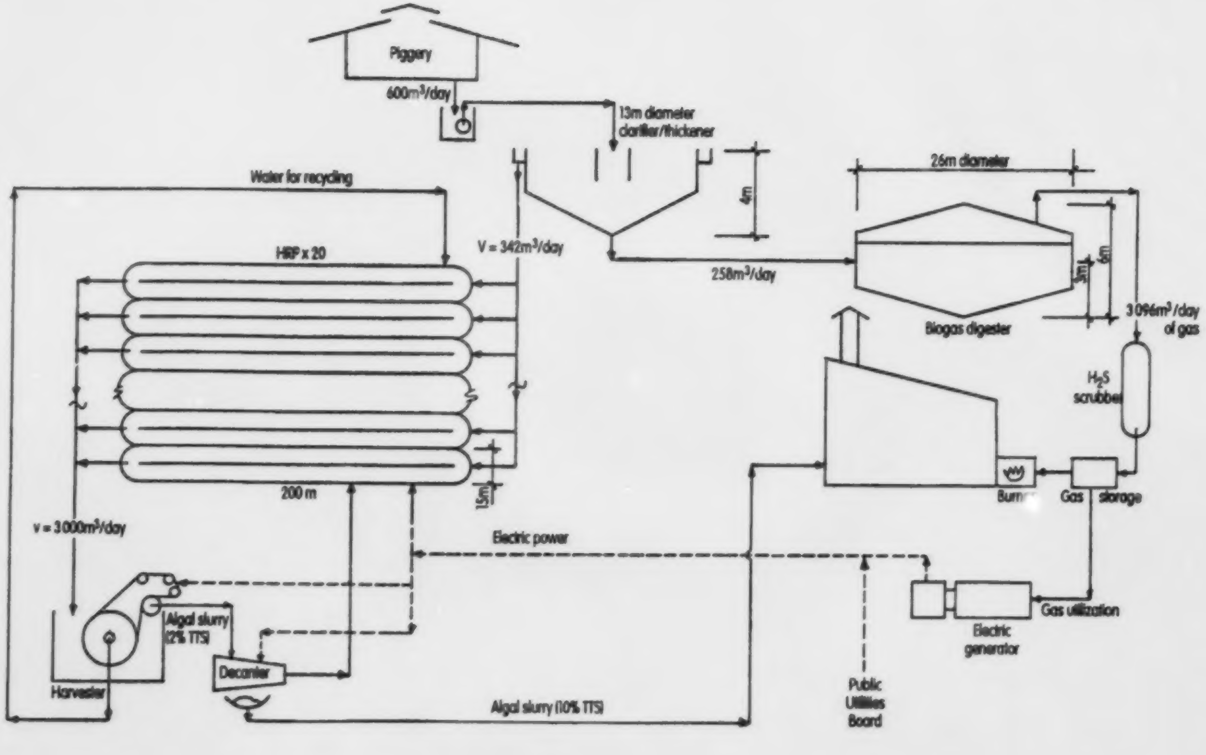
Piggery
600m³/day
13m diameter clarifier/thickener
4m
26m diameter
Water for recycling
V = 342m³/day
HRP x 20
258m³/day
3m
6m
3 096m³/day of gas
Biogas digester
H₂S scrubber
200 m
1.5m
v = 3 000m³/day
Electric power
Burner
Gas
storage
Gas utilization
Electric generator
Algal slurry (2% TTS)
Decanter
Harvester
Algal slurry (10% TTS)
Public Utilities Board

Fig. 7.7. Layout of high-rate algae pond (HRP) system used in the economic feasibility analysis (30 000 SPP).

saving was the cost of operating a plant to treat wastewater to the required standard.

Table 7.13 shows the annual costs and benefits of the system in Fig. 7.7 and compares them with those reported for Thailand and Israel. The comparative data are based on published costs for the two countries, and on an algae system designed for a 30 000-SPP farm in Singapore. The financial analysis was based on several assumptions, too detailed to be enumerated. The assumptions were not the same for all cases. The major common feature was that the area of the ponds was of the same order. The benefits assigned to the Singapore case included cash payments of 1.5 million USD from the government's Capital Grant Scheme (CGS, see Chapter 1) for building a treatment plant to meet existing effluent standards and the benefit of 9 USD/SPP per year, which would have to be spent on the required wastewater treatment operation.

The internal rate of return with all the assumptions on costs and benefits was 18% for Singapore, but it fell to only 6% if a 20% increase in capital costs was assumed. The internal rate of return fell to 11% if no benefit was assigned to the recycling of treated water.

Questions and Answers

Algae Toxicity

Question 1. How can undesirable species of algae be separated from desirable ones? Should they be removed while they are still in the pond or when they are in the dried powder?

Answer 1. It is not possible to separate algae once they are in the dried powder form. It is almost impossible to separate desirable algae from undesirable ones while they are still in the pond. Theoretically, it might be possible to separate unicellular algae from filamentous ones (assuming one of the two forms is undesirable) by using a filter cloth of a pore size that allows the unicellular algae to pass through.

Fortunately, an undesired algal species appears very rarely, but if it does happen, and it is a blue-green algae, it is advisable to empty the pond and start a fresh culture.

Question 2. Is the appearance of toxic algae, such as *Anacystis cyanea*, and *Anabaena circinalis*, a concern if it is not possible to control the type of algae growing in the ponds?

Answer 2. There are some more toxic algae, such as *Mycrocystis aeroginosa*, *Aphanizomenon*, *Anabaena*, and *Coelosphaerum* spp. All these species appear very rarely in artificial culture systems so their presence in high-rate algae ponds is most unlikely.

Question 3. In managing the quality of potable water, the growth of algae and other aquatic plants is discouraged because they cause taste and odour problems. How much of a problem is this? Is algae harvesting only feasible for protein production?

Answer 3. Only a few algae cause odour or taste problems by themselves; in most cases, the problems are caused by decomposition products of algae. The algae must be removed from water that is to be used for drinking. However, the amounts are so small, that one cannot think of biomass production. If they are not used as a protein source, algae grown on wastewater can be used as fertilizer or for biogas production.

Question 4. Provided toxic algae are excluded, is it necessary or feasible to control algal populations to encourage the dominance of a particular species in the high-rate ponds?

Answer 4. It is not necessary to put too much effort into the control of the algal population. The maintenance of one algal species over a considerably long period is actually not possible. As long as a healthy population of green algae with a high yield and an acceptable protein content and quality can be produced, there is no need to control a particular algal population.

Question 5. How sensitive is algae growth to changes in the environment outside the pond (e.g., sudden change in temperature or weather)? In a pond in which algae are blooming, what natural factors can reverse algal growth? How can these factors be inhibited?

Answer 5. Algae are sensitive to environmental fluctuations. The most important factor is light, because algae are autotrophic organisms that require light for photosynthesis. Sudden temperature changes affect algal growth. However, in a warm climate where sudden or diurnal temperature fluctuations are rare, algal production on a field scale is possible. Sunshine is essential; therefore, any prolonged absence of sunshine would affect the pond critically. Such natural factors cannot be controlled, but can be managed with the aid of a computer and daily husbandry measures.

Question 6. What is the normal concentration of soluble sugar in the algae? Is it sufficiently high to bring about the Maillard reaction during heat processing? In that case, would it be better to process the algae in the dark?

Answer 6. The average concentration of soluble sugars in algae is 1–3%. This amount is sufficient to cause the Maillard reaction when algae are heated excessively. Studies with synchronized algae (*Chlorella*) have shown that the protein concentration in the cells is higher at the beginning of the light phase than at the end, when the amount of carbohydrates increases.

Potential of Algae

Question 7. The protagonists for the use of algal protein as the future protein source always base their arguments on the potential high yield of algal protein and claim that under favourable conditions algae have the potential to produce approximately 10 times as much protein per unit area as soybeans. How practical are such yields? Also, because algae can have one mitotic division per day, does that mean that the maximum harvest efficiency attainable is 50%? In other words, if the algal population is to be maintained, can actual yield only be half of the potential?

Answer 7. Under optimal conditions a daily algal growth of 20 g/m^2 can be achieved. There are no long-term data available on sustained rates of growth in high-rate algae pond systems. Now that years of operation in Singapore have shown that a mean daily yield of 17 g/m^2 can be reached, these yields can be compared with those of conventional crops. Based on the yield of crude protein (TKN × 6.25), the comparative annual yields are 30 t/ha for algae, 0.5 t/ha for peanut, 0.3 t/ha for wheat, 0.2 t/ha for rice, and 0.1 t/ha for milk. Algae therefore have a potential value provided extensive area is used and a market is developed.

As for the second part of the question, under optimal conditions, most unicellular algal species divide into at least four daughter cells in 24 h, not just once as was assumed in the question.

Feeding of Algae

Question 8. In the experiments carried out with broiler chickens given diets that contained drum-dried algae, feed intake was reduced because impacted beaks were caused by the hygroscopic nature of the algae. The diet containing algae could also have had low palatability and poor digestibility. Have these three factors limited the utilization of algae elsewhere?

Answer 8. In feeding trials using algae, it is best to feed the algae in pellet form to help overcome the problem of impacted beaks. In controlled experiments elsewhere, when drum-dried *Scenedesmus* and sun-dried *Spirulina* were fed in pellet forms at algal levels of 20–25% (substituting approximately two-thirds of the protein), there were no negative effects.

Question 9. Rats have a large caecum where microbial action takes place to aid cellulose digestion. Therefore, they can utilize algae better than poultry and pigs. How relevant are results from feeding trials with rats when they must be extrapolated to illustrate their value to monogastric animals?

Answer 9. The caecum in rats is located at the end of the intestinal track just before the rectum. Therefore, only a very limited absorption takes place. Furthermore, the microbial action in the caecum aids carbohydrate digestion more than protein digestion. The contribution of microbial cellulase digestion in the caecum is very small and does not significantly influence the values obtained in protein uptake and digestibility experiments.

Question 10. Drum drying of the algal slurry takes much more energy than steam cooking. What cooking conditions are best for feed quality? Are there any problems with wet feeding experiments with rats?

Answer 10. In an algal project in Dortmund (Germany) on the influence of cooking time on the nutritive quality of *Scenedesmus*, it was concluded that a cooking time of 10 min should not be exceeded. Experiments with rats fed boiled algae have shown that the digestion of these algae was less when compared with drum-dried material.

Question 11. To harvest algae by the dissolved air flotation method, flocculants such as alum were used in Israel. In India, a natural flocculant called chitosan was used. Are there any problems with these?

Answer 11. In general, flocculants other than aluminum are preferred. Experiments using the natural flocculant chitosan, obtained from the deacetylated exoskeleton of shrimps, showed it was better. However, researchers in Israel, who have used aluminum flocculated algae, claim that the amount of aluminum flocculant does not affect the performance of chickens, even if the algae are added to the feed at a level of 50%.

Total Recycling

Question 12. The high-rate algae pond system is a component of a complete recycling system in which the water separated from the algae during harvesting is reused to flush the pig barns and recycled through the ponds. Are there any problems with accumulation of salts, toxicity, or colour?

Answer 12. In 1984, total hydraulic recycling without algae harvesting (representing the worst situation) was monitored continuously for a period of 3 months. Thirteen parameters were monitored.

Biogas production was not affected. There was an accumulation of salts in the ponds. Parameters that showed the highest degree of accumulation were chemical oxygen demand, dissolved fixed solids (which is a measure of salts build-up), total ammonia nitrogen, and total solids. There was a net loss of organic nitrogen.

The system started to smell and the colour of the ponds changed from green to brown after approximately 8 weeks. Dissolved fixed solids reached a maximum concentration of 950 ppm. Although a heavy rain diluted the solids concentration, the ponds had not recovered 3 weeks after the rain, and they had to be emptied and restarted. In experiments elsewhere, continuous recycling of effluents from harvesting processes decreased algal growth. This might be caused by the accumulation of growth-inhibiting compounds in the medium. Therefore, 20–30% of the effluents must be replaced by fresh medium or tap water.

Nutrient Uptake by Algae

Question 13. Are algae limited to the use of inorganic nitrogen? When growing heterotrophically, can they use amino acids or do they deaminate and use ammonia? How can the heterotrophic ability of the system be improved? How can the algae be cushioned against sudden environmental changes?

Answer 13. Algae are not limited to the use of inorganic nitrogen. A common organic nitrogen source is urea, which is used for mass cultivation of *Scenedesmus*.

Many algae are capable of using amino acids directly. It is assumed that the acids undergo transamination and that some of them will be introduced, via pyruvate, into the Krebs Cycle for further metabolism. A high concentration of ammonia is toxic to most algae; therefore, the cell will incorporate free ammonia into glutamic acid as part of the formation of glutamine. Because the amount of amino acids in an algal culture medium is normally negligible, the nitrogen of these amino acids does not make an important contribution to the common nitrogen sources for algal cultivation.

Glucose can be used by all algal species as an additional carbon source that can substitute for photosynthetic CO_2 fixation. However, in the Singapore system, which had a high concentration of bacteria in the medium, the addition of glucose was not advisable because it would have been used mainly by the bacteria.

It is not possible to protect the algae against changes in the physical environment by modifying factors such as light or temperature. Only modifications to the chemical composition of the culture medium can cushion the algae against these influences. Lowering the load or varying the detection time seem to be the only practicable methods.

Question 14. Do algae photosynthesize through the usual Calvin Cycle (C_3) or through the Hatch and Slack Cycle (C_4)?

Answer 14. Algae photosynthesize through the Calvin Cycle. Actually, Calvin used the green algae *Chlorella* for his studies, which resulted in the definition of the reductive pentose phosphate pathway.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Comparison of potential yield of algae as a source of protein with local or regional traditional sources of protein.
2. Comparison of algae as a method of pollutant removal with local traditional methods.
3. Comparison of mechanical versus chemical harvesting and processing of algae for refeeding purposes.
4. Assessment of the nutritive value of algae in comparison with other materials.
5. Design and costing of a high-rate algae pond system for pollution control, resource conservation, and recycling.

Chapter 8

Recovery of Fungal and Bacterial Biomass

This chapter was written mainly for engineers not familiar with the terminology, time-consuming procedures, and potential of solid and liquid fungal fermentations. The results of the two methods of fermentation and of the feeding trials will interest scientists who work with fungi. The chapter describes the long-term operation of in-barn oxidation ditches and the use of bacteria biomass as pig feed.

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Methods of Nutrient Recovery from Wastes

One rationale for studies on biomass harvesting from bacterial and fungal fermentation was that approximately 540 000 t of feed was imported into Singapore in 1978 for a standing pig population (SPP) of 820 000. It was estimated on the basis of TKN that the pig excretions were equivalent to 60% of the amount of crude protein (CP) being imported as feed. The nitrogen and minerals of the pig waste were being discarded and were creating serious pollution problems.

Pig wastes as excreted can be classified physically into three fractions: liquid, particulate, and fibrous. The liquids of the urine and of the feces contain salts and soluble compounds such as sugars, amino acids, and organic acids produced by microbial action in the pig gut. The particulate fraction consists of bacteria from the gut (mostly dead) and some lipid and polysaccharide material. The CP content of this fraction can be as high as 50%. The fibrous fraction contains undigested particles of grain, husks, bran, and other fibrous materials that provide bulk in the diet.

The nitrogen in each fraction is in different chemical forms, so its usefulness to the pig varies. In the soluble fraction, it is largely ammonia, which the pig cannot use. It must be converted to protein. The particulate fraction contains ammonia and protein. The nitrogen in the fibre is mostly unavailable to the pig, and the indigestible fibre could build up in the diet if it was directly refed. There are two approaches to nutrient recovery: physical–chemical and biological.

Physical–Chemical Methods

The most direct method of waste utilization is to feed the feces back to the animals. Fecal matter dried to 10% moisture can contain up to 30% CP. Pig feces were dehydrated and fed to pigs at a level of 10% of the diet and weight gain was not significantly different from the control. Although this method recovered 50% of the TTS excreted, nitrogen recovery was less than half. The digestibility of the protein in this material was less than 30% and fibre could build up with repeated recycling. Cost of energy for the dehydration of the feces was high because the feces as excreted had only 15–20% solids. Therefore, methods that would produce better nitrogen recovery and a more digestible protein were pursued.

Biological Methods

The use of pig waste as a substrate for microorganisms can significantly reduce pollution with concomitant resource recovery. Three groups of organisms were investigated: algae, bacteria, and fungi (see Fig. 1.7, Chapter 1).

Introduction to Fungal Fermentation

Microfungi have a number of properties that make them useful for nutrient recovery:

- Growth rates are fast, with a doubling time of 2–6 h. This doubling time is slower than that of bacteria but faster than algae. Fast growth means less detention time and, therefore, a smaller volume of fermentation vessels is required to treat a given quantity of waste.
- Microfungi have a filamentous structure. This allows separation from liquid waste by a rotary vacuum or filter. Filaments also give structure to the food.
- Microfungal protein can have a high nutritive value; therefore, they could replace soybean and fish meal, which are expensive protein components in pig feed. Fungi yield biomass that contains less protein than bacteria or yeasts. In general, from 100 g of carbohydrate substrate, the maximum practical yield of protein from bacteria is 35 g and from yeasts and fungi is 25 g.
- Fungi cell walls are stronger than those of bacteria but do not prevent digestion of the protein by nonruminants. Bacteria cell walls break down readily, but algae cell walls are not digestible unless ruptured.
- Microfungi produce a wide range of enzymes and can therefore adapt to many substrates.

The two major methods of fungal fermentation are submerged (or liquid) and surface (or solid) culture.

Submerged or Liquid Fermentation

In submerged or liquid fermentation, the food or medium in solution or suspension is placed in an enclosed vessel, which is usually steam sterilized to kill organisms that may interfere with fungal growth. An inoculum of the required fungus is introduced into the vessel and, because the process is generally aerobic, air is blown into the vessel. Stirring brings food and oxygen in continuous contact with the matter being fermented and, sometimes, temperature and pH are controlled at levels suitable to the fungus. After 1 to 7 days, depending on the type of fermentation, the microfungus is harvested by filtration.

Surface or Solid Fermentation

In surface or solid fermentation, the medium that is inoculated with the desired fungus is spread on the substrate in shallow trays to expose a large surface area to oxygen. The fungus grows in 2 or 3 days. Gaseous exchange is limited to the surface; therefore, the rate of growth is much slower than in submerged culture. However, less energy, if any, is required. Mixing is limited to exposing a new surface every 1 or 2 days.

This method was originally used with liquid media to produce antibiotics and organic acids. It has been superceded by submerged culture, which can give much higher rates of production because of the increased surface area of the organism in contact with the medium and the avoidance of locally high concentrations of product that suppress fungal activity. However, the method has survived in certain food fermentations such as tempeh (fermented soybean), mushrooms, and protein enrichment of cassava.

The medium is usually in a moist-solid state (about 50% moisture) that exposes a greater surface area than a liquid. The organisms used, such as *Rhizopus* in tempeh, can grow under a very low partial pressure of oxygen. Growth is, therefore, by "fermentation" and by-product alcohols and esters are produced. In fact, many food fermentations have evolved to improve the organoleptic properties of the materials rather than alter fundamentally the nutritional value of the product. In the process, useful vitamins can be produced by the microorganisms.

Application to Pig Waste

The published literature on pig waste gives various values for the composition and quantity of material excreted. This is not surprising given the wide range of factors such as climate, pig type, weight, and feed. In Singapore in 1978, approximately 135 000 t of waste on a dry basis (TTS) were produced during the year. If only the feces and urine were collected, the material would be a slurry with approximately 10% TTS. In Singapore, this slurry was diluted with washwater to give, each day, 20 L/SPP rather than the 4.5 L/SPP excreted. Thus, the concentration of TTS fell to 2% or less.

For moist-solid or surface fermentation, feces with 30% TTS were obtained by separating the feces and urine after excretion and scraping the feces to one end of the barn. The material was mixed with a dry carbohydrate source (1.5 kg TTS of waste with 1 kg of carbohydrate) to give approximately 50% TTS, sterilized, and fermented. Sterilization was necessary to reduce the number of competing bacteria in the waste so the microfungus could establish itself.

The moisture content was critical: if it was too high, bacteria predominated; if it was too low, fungi grew sparsely. The fermentation was carried out in a room at ambient temperature, but the relative humidity was maintained close to 100%. After 3 days, fermentation produced a cake of fungi and original matter. This caked mixture was dried in an oven to kill the microfungus. If this was not done, fermentation continued because of the high ambient temperature and nitrogen was lost by deamination.

For liquid fermentation, the diluted wastewater was accepted "as is" (i.e., 1–2% TTS). It was mixed with 0.5–1% carbohydrate, sterilized in a suitable vessel, inoculated, and fermented for 1 or 2 days. The temperature was maintained at 32°C, which is close to the optimum for many fungi and also close to the daily high temperature in Singapore. The pH was controlled at 6.5.

Many fungi have a tendency to produce organic acids that decrease the pH and distort the mycelium of the fungus. Dissolved oxygen (DO) was controlled by altering either the volume of air blown through the liquid or the rate of agitation. The product was harvested from the spent liquid using a vacuum-filter or belt-filter press.

The sterilization step was expensive. One suggestion was to use thermotolerant organisms operating at 45°C and low pH to reduce the need for sterilization. However, there was no significant difference in the rate of contamination with thermophilic or mesophilic organisms. Low pH initially decreased contamination; however, after a few months, acidophilic organisms started to establish themselves. Heat would be required to maintain a temperature of 45°C, and would offset the savings from not using sterilization.

Nitrogen Recovery

The most important element in fungal fermentation is the recovery of nitrogen in the form of true protein or amino acids because pigs cannot utilize ammonia nitrogen.

When the feces were collected for solid fermentation, some urine was included. The mixture contained approximately 60% of the nitrogen excreted. In small-scale trials, it was possible to get material with 30% TTS. It was estimated that in large-scale systems (a farm), the material would be 15–20% TTS. Nitrogen recovery in such a solids-handling system would be 15–80% of the nitrogen excreted.

If a handling system for liquid waste was adapted along with submerged fermentation, virtually all the nitrogen could be recovered, provided losses in transmission from the farms to the fermentation site were kept to a minimum. At one of the sampling points in the Ponggol PFA that drained 100 000 SPP, 80% of the nitrogen excreted was present, but the percentage of ammonia was much higher than when the waste was excreted. If nitrogen recovery is the main objective of a waste-handling system, it is advisable to minimize storage and use the waste as soon after excretion as possible. Storage of waste in cesspits causes some nitrogen losses through anaerobic decomposition. In liquid systems, the main aim is to convert the ammonia and amino acids to high-value protein and to entrap bacterial floc that are not used in the mycelial net. The floc contain valuable protein.

Method

The first step was to identify the best fungus for fermentation of pig wastes. The criteria for selection were fast growth rate; high protein content; good feed value of protein; no production of mycotoxins; good growth on pig waste; production of few by-products (i.e., yields mainly mycelium); and stable in storage.

Unfortunately, it was not possible to obtain such an organism from a culture collection. Not many organisms had been tested on pig waste and their properties documented. It was necessary, therefore, to carry out a screening program that entailed the following steps.

- *Isolation:* isolation of pure strains of microfungi from natural habitats such as soils treated with pig waste.
- *Screening:* comparison of rates of growth and protein content of the isolated strains on pig waste substrate.
- *Process development:* refinement of the fermentation process using the best isolates from the screening process.
- *Feeding trials:* production of sufficient quantities of fermentation products for feed trials.

Fungal Fermentation Procedures and Equipment

Isolation Medium

Fungi are distributed widely and are generally found as spores, although active growth may be seen on mouldy bread or rotting wood. The difficulty is to isolate the desired organism from the millions of other organisms in the vicinity. This was done by spreading a thin suspension of material such as soil or moulding bread onto an agar plate that contained nutrients. The spore or propagule grew during incubation into a colony, which was then reisolated for purification.

At first, an attempt was made to compose a solid medium containing pig waste. However, when this medium was used for isolation, the plates were overgrown with bacteria. After several attempts, a medium containing 100 mg/L of chloramphenicol (to suppress the bacteria), agar, and soluble starch was developed.

The 140 strains isolated were grouped into four main genera: *Aspergillus, Rhizopus, Fusarium,* and *Penicillium*. A number of possible sterile mycelial forms and a species of *Trichoderma* were also isolated. Generally, *Rhizopus* grew well on the starch wastewater agar, and covered the plates in 3 days. The *Trichoderma* species reached a maximum diameter of 5.6 cm. Strains of *Fusarium* and *Aspergillus* reached a maximum radial growth of 2.7 cm within 3 days. *Penicillium* and the sterile mycelial forms showed slow growth; a few strains of sterile mycelia reached a maximum diameter of 2.0 cm.

There was a significant difference in rate of radial growth between *Rhizopus* and the other genera. However, trials in shaken flask cultures were carried out on all fungi that showed any degree of growth, because an organism with a low radial growth rate on a plate might have a high growth rate in submerged fermentation. The important factor was whether growth on pig waste medium would be suppressed by toxic products or the lack of a special nutrient.

Storage of Isolates

Microfungi are living organisms that, if not maintained, will eventually die. Viable cultures can be maintained for several months, in most cases on malt-extract agar slants in universal or medical flat bottles. However, this is only a temporary form of storage because the organisms can undergo genetic change and degenerate after repeated transfers. A stock culture that would maintain the correct properties of the organism was needed. Thus, a freeze-drier was purchased to store isolated cultures as small lyophils. Under conditions of very low moisture and high vacuum, spores can be stored for many years.

Shaken Flask Screening

For submerged fermentation, the fungi were screened in liquid fermentation vessels. However, a preliminary assessment was carried out with shaken flasks. In liquid fermentation, the important elements are the organism itself, the medium, sterilization, and environmental factors. With pig waste as a medium, most salts were sufficient, but carbohydrates were lacking. The important environmental factors (pH, temperature, and DO) could all be controlled by the commercial fermenter purchased for these studies.

When spores were inoculated directly into pig waste medium, growth was poor and the spores clumped together and developed few growth points. Therefore, the organism was first grown in a synthetic, soluble medium to give vigorous mycelial growth, then transferred to a pig waste medium. The composition of the medium is given in Table 8.1.

To aerate and mix the liquid medium for growth on a small scale, the

Table 8.1. Shake flask inoculum medium.[a]

Component	g/L
Starch (soluble)	20
Ammonium sulfate	4
Potassium hydrogen phosphate	10
Yeast extract	2

[a] Adjust pH to 6.5; dispense 40 mL in 250-mL shake flask; sterilize for 15 min at 1 kg/cm^2 pressure; inoculate with 2 mL of spore suspension.

medium was sterilized in a conical flask, inoculated with the desired microfungus, and incubated on a rotary shaker at 32°C. Initial tests were carried out on a small rotary shaker at about 150 rpm, but mycelia tended to stick to the wall of the flasks. A new shaker that ran at 200 rpm produced a good inoculum.

Early qualitative experiments showed that additional carbohydrate was necessary for good growth of microfungi, probably because of the low level of available sugars in pig waste. A quantitative experiment was carried out to compare 1 and 2% tapioca (cassava), a readily available carbohydrate source in the tropics. The premise was that organisms that could hydrolyze and use starch could also use free sugars. The converse of this argument is not always true. Thus, the effects of using tapioca, glucose, or molasses as a source of energy were studied in detail.

Screening of isolates was started on a medium of 2% tapioca in pig wastewater. This gave thick growth with the limited oxygen transfer of a shaken flask and controls were difficult to filter. The medium was changed to 1% tapioca and diluted pig waste.

Microfungi were selected for good growth and high nitrogen content, which was based on weight (milligrams) of TKN recovered in the product per unit volume (100 mL) of medium. All isolates were tested twice, and those that were consistently above the control were also tested in the fermenters. The isolates that were studied are listed in Table 8.2.

The shaken flask was a comparatively crude test because pH and DO controls were limited. As a result, this step screened out mainly slow-growing organisms. Nevertheless, the number of isolates was reduced from 140 to 30 for testing with the 14-L fermenters.

Submerged Fungal Fermentation

A fermentation jar filled with 10 L of pig waste medium was sterilized in a large autoclave. After it cooled, the jar was inoculated with a shake-flask inoculum (750 mL), stirred, and aerated. Air rate and stirring were varied to maintain DO at 40% saturation. The pH was controlled at 6.5 by the addition of caustic soda. At the end of the fermentation, usually 24–48 h, the product was harvested by filtration through a nylon fabric and dried at 100°C.

The medium used initially was the original shaken flask medium of 2% tapioca and full strength algae-tank pig wastewater. Higher oxygen transfer in the stirred fermenter allowed the use of a stronger medium. Carbohydrate content was reduced to 1% for isolate testing. Many organisms grew well on this medium showing that there were sufficient trace minerals from the pig waste.

Table 8.2. Best microfungi from shake flask testing.

Fungus		mg TKN/100 mL	
Genus	Code	Inoculated medium	Uninoculated control
Rhizopus	001	100	83
Aspergillus	006	101	83
Aspergillus	008	121	83
Aspergillus	009	33	22
Aspergillus	011	122	83
Aspergillus	012	41	22
Aspergillus	019	46	22
Trichoderma	033	53	22
Aspergillus	035	105	83
Aspergillus	036	57	22
Sterile mycelium	039	110	83
Fusarium	040	35	22
Fusarium	046	94	83
Penicillium	055	48	22
Penicillium	059	111	83
—[a]	069	110	83
Penicillium	070	100	83
Rhizopus	071	96	83
Penicillium	078	106	83
Penicillium	079	115	83
Sterile mycelium	080	116	83
Sterile mycelium	083	119	83
Aspergillus	092	97	83
Aspergillus	104	121	83
Aspergillus	108	99	83
Aspergillus	109	104	83
Aspergillus	111	111	83
—[a]	116	105	83
Aspergillus	118	124	83
Cladosporium	137	111	83

[a] Genus not identified.

Isolate Testing Criteria

Twenty-three isolates were chosen from the shaken-flask testing to be suitable for liquid fermenter studies. Of these, 20 isolates were tested at least once. Some of the promising isolates were tested several times in process development experiments. The performance of the isolates was compared on the basis of crude protein (CP), product yield, nitrogen recovery, and COD reduction. For comparison, these variables were expressed as a percentage of total solids (% TTS). Based on these criteria, 10 fungi were selected for full testing (Table 8.3).

Crude Protein

Crude protein was calculated as TKN × 6.25.

Table 8.3. Best microfungi from liquid fermenter studies.[a]

Fungus		CP	PY	NR	CODR
Genus	Code	(% TTS)	(% TTS)	(% TTS)	(% TTS)
Aspergillus	009	28	55	60	86
Aspergillus	019	33	60	69	84
Aspergillus	092	27	63	74	88
Aspergillus	111	33	52	95	88
Rhizopus	001	30	71	75	75
Penicillium	055	28	57	70	89
Penicillium	069	30	63	67	84
Fusarium	046	26	56	60	86
Aspergillus	104	28	65	65	85
Aspergillus	109	32	60	60	82

[a] See list of Acronyms and Abbreviations for definitions.

Product Yield

The addition of carbohydrate to the waste was expensive; to be worthwhile, it would have to result in the highest possible yield of microfungus. Some organisms produced many by-products such as soluble organic acids that produced a high BOD in the effluent and poor product yield. The best overall measure of yield was grams of dry product produced from 100 g COD. Normally, COD was higher than the available carbon in the end product. However, it was used as a comparison parameter because it was routinely monitored.

Nitrogen Recovery

Nitrogen recovery is a combination of the two previous parameters. The total nitrogen recovered in the product was expressed as a percentage of the TKN in the fermenter at the beginning of fermentation.

COD Reduction

Reduction of COD was important because the fungi fermentation process was intended to be one of the unit operations of the pollution control system.

Effect of Carbohydrate Source

The carbon to nitrogen (C:N) ratio in the pig waste was sufficient for fungi growth. The normal C:N ratio required for fungi is 20:1 to 30:1. The carbon content was estimated by dividing the BOD_5 of the medium by 0.66. The C:N ratio of the pig wastewater used in the fermentation studies was 16:1 (i.e., better than needed for good fungal growth). However, tests showed that unless readily available carbohydrates were added, fungal growth was poor. Apparently, the level of free sugars in the pig waste was very low, which prevented the early emergence of enzymes needed to break down the more complex carbohydrates in the pig waste.

Table 8.4 shows the results of typical tests. Tapioca addition at 5 g/L

Table 8.4. Effect of source and level of carbohydrate in substrate.[a]

Fungus and carbohydrate[b]	COD Initial (g/L)	COD Yield (g/100 g COD)	CP (% TTS)	PY (% TTS)	NR (% TTS)	CODR (% TTS)
A1	13.0	5.5	28	42	47	86
A2	11.0	4.0	34	38	77	87
A3	16.7	10.6	32	63	54	83
A4	18.6	10.0	33	54	56	77
B1	13.2	7.8	33	59	77	81
B2	10.8	5.9	36	55	66	86

[a] See list of Acronyms and Abbreviations for definitions.

[b] A1, *Aspergillus* 009 with 10 g/L tapioca; A2, *Aspergillus* 009 with 5 g/L tapioca; A3, *Aspergillus* 009 with 5 g/L glucose; A4, *Aspergillus* 009 with 8 g/L molasses; B1, *Aspergillus* 019 with 10 g/L tapioca; B2, *Aspergillus* 019 with 5 g/L tapioca.

was necessary. The highest product yields were obtained with glucose and molasses. However, in terms of the four test criteria, the results were similar: CP averaged 33% of dry matter (TTS); product yield was 52% TTS; nitrogen recovery was 63% TTS; and there was an 83% reduction in COD.

Degree of Sterilization

In the majority of the tests, the pig waste medium was autoclaved. On a large scale, this would be expensive. Costs to produce steam would be high and capital costs would also be increased because the fermenters would have to be pressure vessels. Unsterilized pig waste could not be used because of the very high bacterial count in the starting material. Tests demonstrated that it was sufficient to boil the medium at 100°C for 1 h.

Sterilization for 30 min was inadequate, even when the temperature was raised to 129°C. This revealed the weakness of autoclaving the pig waste medium. The heavy solids settled to the bottom of the fermenter and heat penetration was poor. Without mixing, some bacteria survived in the solids and floc. This was noticeable when fermentation with thick waste (3–6% solids) was attempted. Losses through contamination were much higher. Sparging steam into the medium until it was boiling vigorously for 1 h was not a successful method of sterilization because transfer of the medium to the fermentation vessel was difficult.

Control of pH

In most fermentations, pH was maintained at 6.5, which is close to optimum for most microfungi. Some of the microfungi had a tendency to produce an acid environment; therefore, several runs were carried out without pH control to see the effect of allowing the pH to fall naturally from the initial level of 6.5 (Table 8.5).

Table 8.5. Comparison of liquid fermentation with and without pH control.[a]

Genus	Code	pH	Time (h)	CP (% TTS)	PY (% TTS)	NR (% TTS)	CODR (%)
Aspergillus niger	036	6.5	47	23	50	—	75
		6.5–3.5	28	16	60	—	80
Penicillium	055	6.5	47	27	61	80	92
		6.5–5.5	30	31	51	55	92
Aspergillus	035	6.5–4.4	53	23	66	59	86
Aspergillus	109	6.5	28	33	63	68	81
		6.5–4.0	52	29	47	56	70

[a] Time, duration of test run; see list of Acronyms and Abbreviations for definitions.

The results were not strictly comparable because the medium was different on each occasion, but the response was variable. *Aspergillus niger*, an acid-producing organism, did not seem to be affected by the low pH, but its protein content was low in both cases. The medium in controlled pH (6.5) tests for this fungus contained 2% tapioca; only 1% was added in the variable pH (6.5–3.5) test. This may account for the lower product yield and longer running time of the control medium. Nitrogen recovery in *Penicillium* 055 and *Aspergillus* 109 was affected by the low pH, although the fall in pH was only slight. *Aspergillus* 035 gave a similar pattern of low yield and low nitrogen recovery with low pH.

It seems preferable to maintain pH at 6.5, despite the increased costs for instrumentation and chemicals. Low pH did not protect against contamination. Several runs were lost because of bacterial contamination while operating at low pH.

Temperature Control

The fermenters used in these studies had heating and cooling units that maintained the temperature within ±0.5 Celsius degrees. Heat was generated in the fermenter by biological action and agitation. On one occasion, the cooling system failed, the temperature rose to 40°C, and the microfungus died. In large-scale units, only cooling would be required.

Harvesting of Fungi

The microfungi from the 14-L fermenters were harvested by filtering the liquid through nylon. A rotary vacuum filter would be better. The effluent liquid contained only about 10% of the input COD, part of which resulted from the added carbohydrates. COD reduction of the original content of the pig waste averaged 87%. Nitrogen recovery was 70%, which, if recycled to the pigs, could meet 37% of their nitrogen needs.

Drying was done in a laboratory oven. This was rather slow and caused deterioration of the product. To develop a full-scale process, other forms of drying would have to be tried, such as fluidized-bed drying or possibly drum drying. The cake from the filter could also be wet fed.

The 10 microfungi selected from the screening program yielded a product with 28–33% CP and 15–20% ash and fibre. The fibre component was high. If the raw pig waste was passed through a vibrating screen to remove bran before fermentation, the amount of fibre in the final product would be reduced. Ash was fixed by the level in the pig waste and could not be reduced significantly. When the product was resuspended in water and refiltered, ash decreased by only 1%. Therefore, very little was free salt. The ash contained minerals such as calcium and phosphorus.

Solid Surface Fungal Fermentation

Small-Tray Fermentation

In the initial studies with solid fermentation, pig wastewaters were dried to 80% solids, mixed with starch, diluted with water to give 50% moisture, sterilized, and inoculated. Later, fecal solids were collected and the moist pig waste was mixed with tapioca on a 5 to 1 wet weight basis. The mixture was dispensed in small aluminum trays (200 g/tray), sterilized, and inoculated with 10 mL of spore suspension from a medical flat bottle. Incubation at 30–35°C produced vigorous growth in 3 days.

This method was used to test 130 isolates for growth and crude protein. Initially, the isolates were screened qualitatively for extensive mycelial growth. From the first test, 89 organisms that showed good growth were retested. The 36 organisms with good mycelial growth are listed in Table 8.6. Higher CP indicates utilization of the added carbohydrate, loss in weight of the substrate, and, therefore, microfungal growth.

Amino Acid Profile

In solid surface fermentation of raw pig waste, there were no marked changes in the product yield of crude protein or true protein; however, there was a significant change in the amino acid profile of the fermented product. This means that the nutritive quality of the fermented waste product improved. The microfungi isolates that were selected for amino acid analysis are listed in Table 8.7, along with the results of the analysis. Two of the isolates, namely *Rhizopus* 001 and 051, produced amino acid profiles comparable with FAO standards. *Rhizopus* 051 was chosen for larger scale testing.

Sterilization

A few experiments were carried out to check minimum sterilization conditions. Sterilization reduced the bacterial population of the pig waste. Fungal growth was inversely proportional to the bacterial count on the

Table 8.6. Screening of fungi isolates for surface fermentation.[a]

Fungus			
Genus	Code	Growth[b]	CP (% DM)
Control	—	—	17.47
Rhizopus	051	++	18.08
Control	—	—	13.49
Penicillium	064	++	15.27
Sterile mycelium	065	+	15.49
Fusarium	075	+	15.82
Control	—	—	14.14
Aspergillus	049	++	14.44
Aspergillus	057	++	14.78
Penicillium	064	++	14.88
Control	—	—	15.06
Aspergillus	056	++	17.13
Aspergillus	077	++	16.06
Control	—	—	14.40
Rhizopus	081	++	15.05
Rhizopus	087	++	14.66
Rhizopus	090	++	14.60
Rhizopus	091	++	14.93
Control	—	—	14.02
Rhizopus	001	++	18.31
Rhizopus	002	++	19.82
Penicillium	079	++	16.95
Sterile mycelium	080	++	16.48
Fusarium	085	++	16.53
Aspergillus	092	++	16.72
Mucor	093	++	16.51
Aspergillus	094	++	16.46
Control	—	—	13.29
Aspergillus	099	++	16.87
Aspergillus	100	++	17.89
Rhizopus	101	++	16.56
Penicillium	105	++	15.31
Aspergillus	106	++	15.26
Aspergillus	107	++	14.36
Aspergillus	109	++	15.16
Control	—	—	13.57
Rhizopus	088	++	16.78
Penicillium	112	++	15.37

continued

Table 8.6 concluded.

Fungus			
Genus	Code	Growth[b]	CP (% DM)
Control	—	—	12.96
Rhizopus	014	++	16.47
Rhizopus	096	++	15.41
Fusarium	103	++	15.53
Aspergillus	111	++	15.29
Aspergillus	113	++	15.47
Aspergillus	117	++	15.97
Aspergillus	118	++	15.46

[a] Small tray experiments with pig wastewater were supplemented with 20% tapioca as an energy source. Of the 89 fungi tested, only those with good mycelial growth are listed here.

[b] Growth was estimated visually: +, good; ++, very good.

surface of the lumps. The objective of the experiment was to ascertain whether the bacterial population could be managed with limited sterilization of the medium.

Sterilization at 100°C resulted in marginally less growth than at 121°C, but was acceptable. The bacterial count deep inside the lump was still high, but it did not affect fungal growth. A sterilization temperature of 60°C for 1 h was insufficient.

Large-Tray Fermentation

For pig refeeding trials, large quantities of material were required. Part of a laboratory was converted into a high-humidity chamber and large trays (100 cm × 30 cm × 12 cm) were held in a rack. Each tray could hold 10 kg wet weight of pig waste plus tapioca. *Rhizopus* 051 was used for the first large-scale tests to build up a stock of material for chicken toxicity tests. The results of some typical experiments are given in Table 8.8. Crude prctein was much lower than in the small-scale fermentations. A fully monitored fermentation was carried out to determine why the changes had occurred (Table 8.9).

Table 8.10 present the results in Table 8.9 on the basis of dry matter. The medium was prepared by mixing 30 kg moist pig feces with 6.6 kg tapioca meal. The weight dropped to 31.1 kg wet solids after sterilization. Thereafter, the mixtures to be tested were duplicated in trays that weighed 10, 10, and 11.1 kg. At days 2, 3, and 5, a tray was removed and the product was dried, analyzed, and compared with the control.

There was considerable loss in weight after sterilization, but this was mainly water. The dry matter difference could be an artifact because it was difficult to ensure that samples did not change in moisture before analysis. The whole tray could be weighed after the fermented material was dried to give an accurate measure of moisture. During fermentation, there was

Table 8.7. Amino acid composition (g/100 g crude protein) of pig waste fermented with selected strains of fungi.

Amino acid	*Rhizopus* 001	*Rhizopus* 002	*Aspergillus* 006	*Rhizopus* 051	*Aspergillus* 099	*Aspergillus* 100	*Rhizopus* 101	FAO[a]
Essential								
Arginine	3.66	2.52	2.39	2.11	2.43	2.63	3.08	—
+Cystine	3.93	3.63	3.68	—	2.61	2.29	2.96	1.20
Histidine	2.08	1.26	1.42	2.11	1.42	1.51	1.57	—
Isoleucine	2.95	2.17	1.99	2.11	2.37	2.63	2.23	4.20
Leucine	4.81	4.24	4.61	3.08	4.51	3.75	4.47	4.80
Lysine	5.19	3.23	3.01	2.38	3.08	2.85	3.74	4.20
Methionine	1.26	0.86	0.68	3.89	0.89	0.67	0.72	2.20
Phenylalanine	2.84	2.72	2.73	2.33	2.55	2.24	2.72	2.80
Threonine	3.06	2.42	2.67	2.54	2.79	3.35	3.74	2.80
Valine	3.50	2.67	2.50	—	2.31	2.79	3.02	4.20
Nonessential								
Alanine	3.17	3.03	3.47	4.16	2.85	3.41	4.29	—
Aspartic acid	4.81	4.69	3.98	4.16	4.68	6.65	6.88	—
Glutamic acid	14.42	12.21	13.25	9.41	13.52	11.51	15.40	—
Glycine	3.71	2.37	3.07	3.03	2.43	3.13	3.93	—
Proline	4.04	3.28	3.87	3.35	3.68	3.13	5.07	—
Serine	2.84	1.92	2.73	2.43	2.73	3.02	3.26	—
Tyrosine	2.62	1.77	1.88	1.14	1.84	1.96	2.54	2.80
Total amino acid	68.89	54.99	57.83	52.78	56.69	57.52	69.62	—
Crude protein (% TTS)	18.31	19.82	17.58	18.40	16.87	17.89	16.56	—

[a] Level, suggested by FAO, as the amount of amino acid that should be present in a well-balanced amino acid profile for materials intended for human consumption.

Table 8.8. Results of experiments on the solid fermentation of pig wastes plus tapioca by *Rhizopus* 051.[a]

Test	Medium (kg)	Product (kg)	Crude protein (%)	Crude fibre (%)	Ash (%)	Ether extract (%)	Gross energy (kcal/kg)[d]	Moisture (%)
FP only	30.7[c]	11.2	12.4	15.7	22.9	2.7	3263	—
	25	14.5	13.3	17.9	26.2	1.4	3389	—
	19	11.1	12.8	19.6	26.3	1.8	3535	—
	36.6	12.6	13.6	24.0	27.1	1.1	3306	—
FP vs control								
Control	36.6	—	17.1	19.5	32.9	—	—	43.6
FP	—	12.3	13.7	17.9	25.6	1.8	3542	—
Control	36.6	—	12.0	16.6	28.5	—	—	49.8
FP	—	11.4	12.3	18.8	23.4	1.6	3336	—
Control	36.6	—	14.9	11.5	17.4	—	—	54.6
FP	—	11.8	16.1	15.5	20.6	2.3	3707	—
Control	36.6	—	15.9	11.9	18.2	—	—	54.9
FP	—	—	16.0	15.6	21.2	—	—	2.5
Control	36.6	—	18.2	13.6	37.1	—	—	58
FP	—	—	14.8	12.8	16.8	—	—	—

[a] Moist feces were mixed with tapioca in the ratio 30 kg pig feces to 6.6 kg tapioca or equivalent. The mixture was sterilized for 1 h at 127°C, cooled, spread on trays (10 kg on 140 cm × 30 cm × 8 cm trays), then inoculated with *Rhizopus* pregrown in small trays. The trays were incubated at 30–35°C and 90–100% relative humidity for 3 days (in certain experiments, 1–7 days). The product was then dried, weighed, and analyzed.

[b] FP, fermented product; control, medium without fungal inoculation.

[c] Weight of medium measured "as is."

[d] 1 cal = 4.187 J.

Table 8.9. Material balance during solid fermentation of pig waste plus tapioca by *Rhizopus* 051.

	Weight (kg)	Moisture (%)	Dry matter Product (kg)	Dry matter Control (kg)	Dry matter Loss (kg)	Weight loss (%)
Before sterilization	36.60	56.5	15.90	15.90	+1.10	—
After sterilization	31.10	52.4	14.80	14.80	0.00	0.0
1 day	9.80	—[b]	—[b]	—[b]	—[b]	—[b]
2 days	9.27	55.0	4.17	12.97	1.83	12.4
3 days	8.14	54.5	3.70	11.50	3.30	22.3
5 days	7.51	48.2	3.95	11.07	3.70	25.0

[a] The plus sign indicates a gain, rather than a loss.

[b] There was so little growth after 1 day that the first analysis was performed on the 2nd day.

Table 8.10. Materials balance on a dry matter basis for the data in Table 8.9.

	Crude protein			Crude fibre			Ash		
	TTS (%)	Total batch (kg)	Loss (%)	TTS (%)	Total batch (kg)	Loss (%)	TTS (%)	Total batch (kg)	Loss (%)
Before sterilization	15.0	2.39	+20.0[a]	12.8	2.04	+10.0[a]	19.8	3.15	+9.0[a]
After sterilization	13.4	1.98	0.0	12.6	1.86	0.0	19.6	2.90	0.0
2 days	14.5	1.88	5.0	14.1	1.83	1.6	21.8	2.83	2.4
3 days	15.6	1.79	9.6	16.1	1.85	0.0	23.8	2.73	5.8
5 days	13.6	1.50	24.2	18.6	2.06	0.0	26.5	2.93	0.0

[a] The plus sign indicates a gain, rather than a loss.

a steady loss in weight as the organism utilized the carbohydrate. The visual appearance of the growth agreed with the loss in weight. On the first day, there was very little growth. This was followed by rapid colonization on days 2 and 3. Thereafter, growth slowed because the whole surface was covered with mould. Product inhibition and gas transfer limited growth. However, over this period (3–5 days), there was considerable loss of crude protein. This loss was due to the loss of ammonia from the surface because protein was being broken down by protease that was still active in the lumps of the media. It was therefore important to stop the fermentation at 3 days; after this, the process began to produce undesirable products.

The small trays had a higher inoculum level than the large trays. This may be advantageous and give slightly faster and more even fermentation. The greater mass of material in the big tray produced localized high temperatures on the undersurface of the tray, which restricted fungal growth but allowed bacteria to be very active. The major reason for the lower protein levels in the big trays was the slight change in the moisture of the waste that was used. In the small experiments, the pig waste was drier.

Feeding Trials

The fungal single-cell protein used in the feeding trial was produced from the solid fermentation of pig wastes using *Rhizopus* as the inoculum. Its nutritive value was evaluated with broiler chickens.

The fermented pig waste contained 14% CP and 24% ash. Its inclusion in the broiler diet resulted in depressed growth rate and feed efficiency. At 21% inclusion, growth rate was reduced by 7% and feed efficiency was decreased by 36%.

At the end of the first experiment, five birds from each group were sampled and subjected to pathological studies. The treatment groups had a highly significant incidence of bile duct hyperplasia and cell proliferation in the liver. These findings were consistent with mycotoxicosis. A further trial gave the same results.

Both chicken trials were carried out using *Rhizopus* 051 on a medium that had been autoclaved and fermented for 3 days. In each case, signs of toxicity were found. The Mucorales fungi, of which *Rhizopus* is a member, have never been reported to produce a toxin; therefore, it seemed more likely that the toxin was bacterial. The bacteria in the centre of the lumps were not killed and the anaerobic conditions were ideal for the development of pathogens. To make this fermentation safer, a method must be devised to produce much smaller lumps of medium. The material was difficult to cut at 50% moisture; an extrusion process may be more successful.

Nitrogen Recovery

Figure 8.1 illustrates nitrogen recovery using surface (moist solid) and submerged fermentation. Nitrogen recovery is much higher (71%) with liquid fermentation than with solid fermentation (43% recovery of feed nitrogen). In both cases, the maximum percentage of the daily nitrogen requirement of the pigs that could be met by recycling pig wastes fermented with fungi was less than 37%.

Future Applications of Large-Scale Solid Fermentation

The tray method of surface fermentation could be used on a large scale, but it is very labour intensive and difficult to operate. However, this type of fermentation lends itself to a continuous approach, although the cost is increased. One approach that could be taken is to use fermenters similar to cement kilns.

The tray method is cumbersome because, to obtain good growth throughout the waste, the material should be turned over after 2 days and then manually harvested. It might be possible to use a slowly rotating cylinder with projections inside to lift the fermenting material. This would lend itself to continuous sterilization, fermentation, and drying, with the use of

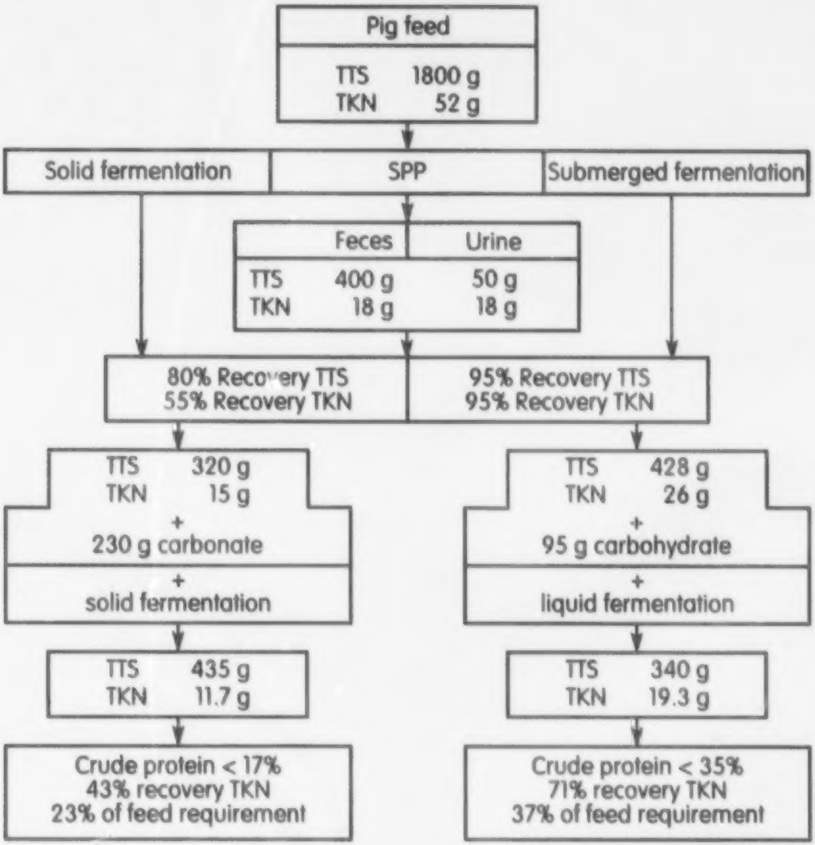
Pig feed
TTS 1800 g
TKN 52 g
Solid fermentation
SPP
Submerged fermentation
Feces
Urine
TTS 400 g 50 g
TKN 18 g 18 g
80% Recovery TTS
55% Recovery TKN
95% Recovery TTS
95% Recovery TKN
TTS 320 g
TKN 15 g
+
230 g carbonate
+
solid fermentation
TTS 428 g
TKN 26 g
+
95 g carbohydrate
+
liquid fermentation
TTS 435 g
TKN 11.7 g
TTS 340 g
TKN 19.3 g
Crude protein < 17%
43% recovery TKN
23% of feed requirement
Crude protein < 35%
71% recovery TKN
37% of feed requirement

Fig. 8.1. Flow of TTS and nitrogen in fungal fermentation.

different residence times in each section. Another method would be to develop a conveyor belt system like the continuous ovens used for biscuit manufacture.

Barns for Aeration Studies

Two existing barns that housed porkers had two rows of pens that were partially slotted. Each of the two barns had capacity for 128 pigs. The pig population was fairly constant. Porkers removed for market were replaced with young growers to minimize variation in the pig population.

The two pits under the slotted floors were connected to form an oval oxidation ditch inside the barns. The pits were 27 m long and 1.6 m wide. Total depth of the pits was 1.33 m. The overflow weir was set at a depth of 1.27 m in the pits, but could be raised by placing boards across the weir.

Two methods of mechanical agitation and aeration of the pit contents were used. A caged rotor (brush aerator) was designed and fabricated locally to suit one of the ditches. Two jet aerators with inclined hollow shafts with propellers at the end of the shafts (Aerob-A-jet) were purchased for the other barn. In the Aero-A-jet system, air was sucked into a hollow shaft and was exhausted below the water surface at the end of the shaft, which was equipped with a rotating propeller.

Continuous organic loading was achieved by allowing the defecated waste to enter directly into the aerated pit and by washing the rest of the feces and spilled feed into the ditch. Both systems developed stable bacterial populations with a good floc structure that settled well and left a clear supernatant.

Bacteria Liquid Biomass Composition

The liquid in the agitated ditch was a mixture of bacteria and volatile solids that together formed the bacterial protein mass to be harvested. The liquid biomass in the oxidation ditch contained about 1.54% dry matter (TTS), 42% of which was crude protein. The ash content was 29% and the fibre content was 10%. The mix also contained 81 ppm nitrates and nitrites.

Liquid Biomass Feeding Trials

In one feeding trial, 160 porker pigs were divided into two groups, each consisting of pigs of similar age, weight, and sex. In the treatment group, bacterial liquid biomass was mixed with dry feed in the ratio 2 to 1 by weight. In the control group, tap water was mixed with dry feed in the same ratio. The trial started when the pigs averaged 50 kg live weight. They were on restricted feeding and a standard 16% CP compound feed was used throughout the trial. The trial ended when the pigs reached 85 kg live weight.

Because of the high moisture content of the bacterial liquid in the oxidation ditch, the solids were concentrated by stopping the aerators for 1 h and thickening the liquid in the ditch. The sludge settled to the bottom. The thickened sludge, which was considered to be a bacterial liquid biomass, was then pumped out from the bottom of the pit and fed to the pigs.

Pigs fed with feed mixed with tap water had a better daily weight gain (0.66 kg) than pigs fed mixed liquid from the oxidation ditches (0.58 kg). The feed conversion ratios were 3.63 and 4.14, respectively. The difference was not, however, statistically significant ($p < 0.05$). The standard errors were considerably larger for the data on pigs whose diets were mixed with bacterial liquid biomass.

A greater incidence of pneumonia was observed in pigs whose diets contained the bacterial biomass. However, no deaths were recorded. No appreciable difference was noticed in the number of visceral condemnations of the pigs in the control and treatment groups when they were slaughtered at the abattoir.

The reasons for the depressing influence of the bacterial biomass in the oxidation ditch liquid on pigs were not clearly understood. The study clearly demonstrated a higher incidence of pneumonia associated with pigs fed the bacterial biomass, although the etiology of the pneumonia was not clear. Another cause could be the high nitrite and nitrate levels. Although nitrate itself is relatively nontoxic, it might be reduced to nitrite by microorganisms resident in the intestines of pigs. Absorption of nitrites into the bloodstream results in the conversion of hemoglobin into methemoglobin because of the oxidation of Fe^{2+} to Fe^{3+} by nitrites. Methemoglobin prevents the transport and release of oxygen by the blood. If a substantial proportion of the hemoglobin was converted, internal asphyxiation would result. The high level of nitrates and nitrites (81 ppm) in the oxidation ditch liquid could pose a potential danger to the pigs.

In view of the great variation associated with the data, particularly the treatment group, the experiment was repeated in 1980. In this study, younger pigs were used to determine whether the oxidation ditch bacterial liquid biomass could be substituted for part of the protein and mineral requirements of grower pigs. The daily weight gain after 18 weeks of testing averaged 0.58 kg/SPP for the pigs fed conventional feed; those pigs that received liquid biomass with their diet (both diets were equivalent in terms of protein content) averaged only 0.53 and 0.50 kg/SPP (8.6–13.8% less than the control diet).

Effect of Nitrites

In the second study, as in the first trial, pigs fed oxidation ditch liquid biomass had significantly less growth and consumed more feed than those on the standard diet. Once again, it was suspected that nitrites might be causing growth depression. Therefore, a feeding trial was run with nitrates removed.

The oxidation ditch bottom liquid was strained and the remaining solids were tunnel dried in a solar drier. The dried bacterial biomass was substituted into the pig diets at 9 and 18% and the performance of the pigs was measured. The pigs tested in this experiment averaged about 35 kg live weight at the beginning of the experimental feeding. After 9 weeks, the control pigs averaged 78 kg (average daily gain, 0.68 kg/SPP). Pigs whose feed contained 9% bacterial biomass weighed 73 kg (6.4% less than the control). The group fed 18% dried bacteria biomass averaged 70 kg (10.3% less than the control).

Apparently, nitrites in the bacterial liquid biomass were not the sole cause of depressed growth. Other factors may have caused the depression in growth when the pigs were fed bacterial biomass harvested from their own wastes, either in liquid or dry supplements.

Table 8.11. Quality of oxidation ditch and lagoon effluent.

	Government standard		Oxidation ditch			Lagoon	
Parameter	Sewer	Watercourse	Avg.	Median	Polishing[c]	Avg.	Median
BOD_5 (mg/L)	400	50	150	80	5–20	318	315
COD (mg/L)	600	100	485	330	89	811	790
pH	6–9	6–9	7.7	—	7.8	7.8	—
TSS (mg/L)	400	50	302	150	16	545	510
TDS (mg/L)	3000	2000	1751	—	—	1585	—

Note: See list of Acronyms and Abbreviations for definitions.

[a] May 1977 to May 1979.

[b] August 1978 to August 1979.

[c] Polishing consisted of dosing the effluent in a 1-L beaker with sufficient alum or ferric chloride to settle the solids. The supernatant was tested for the parameters shown.

Treatment Efficiency

A summary of the effluent quality achieved compared with effluent standards and with a lagoon are given in Table 8.11. The data indicate that the quality of treatment provided by the oxidation ditch was sufficient to meet governmental standards for wastewater discharges to sewers and public water streams.

Oxygen Transfer

The locally fabricated brush aerator was operating at 0.9–1.2 kg O_2/kWh, which was higher than the transfer efficiency of the 3-hp (2.2 kW) Aerob-A-jets that were transferring at 0.5 kg O_2/kWh. Power consumption did not vary much with different immersion, which meant that power consumption was almost constant. The ditch aerated by the brush aerator was operating at a high DO level of 1–3 mg/L. This level of aeration helped control excessive growth of filamentous bacteria, which cause sludge bulking.

Oxygenation Coefficients

Laboratory studies were carried out to determine process variables and their relation to operating parameters. These variables were used in the design of the cage rotor brush aerator. The alpha factor was 1.0; the beta factor was 0.91.

Sludge Age

The sludge volume index of the mixed liquid generated in the oxidation ditch under the slatted floors varied from 64 to 117 mL/g, which favours solids separation using conventional methods. With conventional solids separation, the efficiency of the system for TSS removal was 98% and the mean BOD_5 of the effluent was 70 mg/L.

Final Clarification

Aeration with Aerob-A-Jet

The under-slats aeration system for the waste from 128 growers and finishers operated continuously for several years. The mixed liquid from the pit in the ditch was pumped once a day into a 2.9-m^3 clarifier for separation of solids. After 2 h, the sludge was well separated from the liquid supernatant.

Samples of the effluent were collected three times a week. Frequency analysis of the data from May 1977 to December 1979 (over 350 observations) was carried out. The analysis showed that less than 50% of the time the system had been discharging effluent with BOD_5 and TSS less than 60 mg/L and 120 mg/L, respectively, with an average of 131 mg/L BOD_5 and 275 mg/L TSS.

To reduce the BOD_5 and TSS concentration in the effluent, alum was used as a coagulant. Alum was applied at 1 500 mg/L while the mixed liquid was pumped into the clarifier. Alum reduced the effluent BOD_5 from 131 to 10 mg/L and the TSS from 275 to 28 mg/L. More than 70% of the time, BOD_5 and TSS were less than 10 mg/L and 50 mg/L, respectively, which is well within the limits of effluent water quality standards (see Table 8.11).

Aeration with Cage Rotor

The effluent BOD_5 and TSS were less than 30 mg/L and 69 mg/L, respectively, 50% of the time, and less than 91 mg/L and 140 mg/L, respectively, 80% of the time. With 1 000 mg/L alum, the average BOD_5 and TSS of the effluent were reduced to 9.5 mg/L and 27 mg/L, respectively.

Power Consumption

Power consumption was 0.7–0.8 kWh/kg live weight gain. At 0.10 USD/kWh, the cost of adding 70 kg live weight would be 4.90–5.60 USD per pig marketed. The cost of alum was the major cost incurred in the polishing of the effluent with chemicals. It was estimated that the additional operating cost required to meet effluent standards would be 0.70–1.05 USD per pig marketed.

Sludge Drying

A volume of 3 m^3 of the mixed liquid pumped from the oxidation ditch yielded 0.8 m^3 sludge (1.8% solids concentration) when placed in a sedimentation tank. The thickened sludge was drained into a 2 m × 1 m drying bed. The solids content in the drying bed increased to 14% in 24 h and to 20% in 7 days. The drying beds were loaded at 374 kg TTS/m^2 per year

Table 8.12. Comparison of biomass from fungi, bacteria, and algae treatment systems.

Parameter[a]	Fungi	Bacteria	Algae
PY (% of original TTS)	65	45	20
CODR (% of original COD)	90	99	99
NR (% of original TKN)	50–70	33	24
CP (% TTS)	33	28	55
Ash (% TTS)	15–20	35	10[b]
Fibre (% TTS)	15–20	14	10[b]
TKN recovery	High	Low	Low
Quality of treatment	Low	High	High
Product yield	Low	Good	Low

[a] See list of Acronyms and Abbreviations for definitions.

[b] Ash and fibre are low because they are separated before the process.

compared with the normal loading rate of 121 kg TTS/m^2 per year adopted in local sewage-treatment plants. The drying beds were covered with plastic sheets to prevent rainwater from wetting the dried sludge. However, the cover was not necessary for high-quality sludge, such as that produced by the oxidation treatment in the pits under the slatted floors.

Bulking Sludge

In May 1978, the Aerob-A-jet aerator system was stopped for 1 week. During this period of low DO, filamentous bacteria multiplied and produced a bulking sludge. This was a voluminous sludge that settled poorly. It was impossible to eradicate the filamentous bacteria by maintaining high DO. High DO was achieved by reducing the loading and by wasting more sludge to maintain low solids levels. The best solution was to empty the ditch and restart the growth of the biomass. A small percentage of the population was always filamentous. It is useful to have some filamentous bacteria because they help give strength to the flocs; however, for routine operations, low DO conditions encouraged excessive growth of filamentous bacteria. The higher organisms present in the oxidation ditches were mostly ciliate protozoa. These organisms were observed mainly in the caged rotor brush aerator, where high DO levels were maintained. The effluent was excellent when rotifers and ciliates were found in it.

Nitrogen Recovery

Table 8.12 summarizes the characteristics of the protein recovered from fungal, bacterial, and algal treatment systems.

Chapter 9

Design and Construction of the Ponggol Pigwaste Plant

The Ponggol Pigwaste Plant was designed to treat the wastes from a farm with a standing pig population of 35 000. It included eight unit operations that could be combined to provide different levels of treatment. The cost of construction in 1985 was 2 million USD or 61 USD/SPP. The plant was operated for several years. During the first year of operation, the annual operating cost (AOC) was 2.75–5.83 USD per pig marketed per year. This chapter highlights the steps taken in construction, the design parameters and considerations, the cost of construction, and the cost of operation.

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Purpose of the Plant

The concept for the Ponggol Pigwaste Plant (PPP) was first mooted to a mission from the Australian Development Assistance Bureau (ADAB) in 1979. The idea was to demonstrate wastewater treatment integrated with total resource recovery (Fig. 9.1). The plant was to include the separation and stabilization of solids combined with energy recovery and single-cell protein production as part of nutrient recovery.

The recovery of microbial protein biomass from fungal fermentation was not included in the final plans because of the technical problems encountered in the experimental projects and the economics of the process (as outlined in Chapter 8). The algae ponds were also eliminated because the full-scale, high-rate algae ponds that had been operating at the Pig and Poultry Research and Training Institute had already demonstrated the essential processes of production, pond management, harvesting, and utilization (see Chapter 7).

With the promulgation of pig waste control regulations in 1981, the idea of demonstrating unit operations that could produce effluent with a BOD_5 of less than 50 mg/L was included in the objectives of PPP. Also, it was decided that the plant should be built and operated on a private farm of typical commercial size in Singapore.

With funding from ADAB and Industrial Farm Pte Ltd (IFPL) in the Ponggol pig feedlot farming areas (PFA), the PPP project was officially launched in March 1982. The plant became operational in May 1984, 5 years after the idea was mooted.

Figure 9.2 shows the layout of IFPL, which became the site for the treatment plant. IFPL was developed in two phases. Phase I facilities were constructed in 1975 to house 14 000–15 000 SPP in 36 small barns. Phase II barns were constructed between 1980 and 1983 to house 16 000–20 000 SPP, and consisted of eight barns, each 283 m long. The new barns were engineered to include waste flushing under the slatted floor channels to facilitate easy hydraulic removal of the fresh wastes that would be used to recover energy.

The specific objectives of the project were to construct a plant on a commercial farm that would be used to

- demonstrate various levels of treatment on a large scale,
- integrate the treatment system with resource-recovery processes,
- carry out engineering research and training on the unit operations and treatment processes, and
- evaluate the technical feasibility, environmental impact, and economic costs of different levels of treatment.

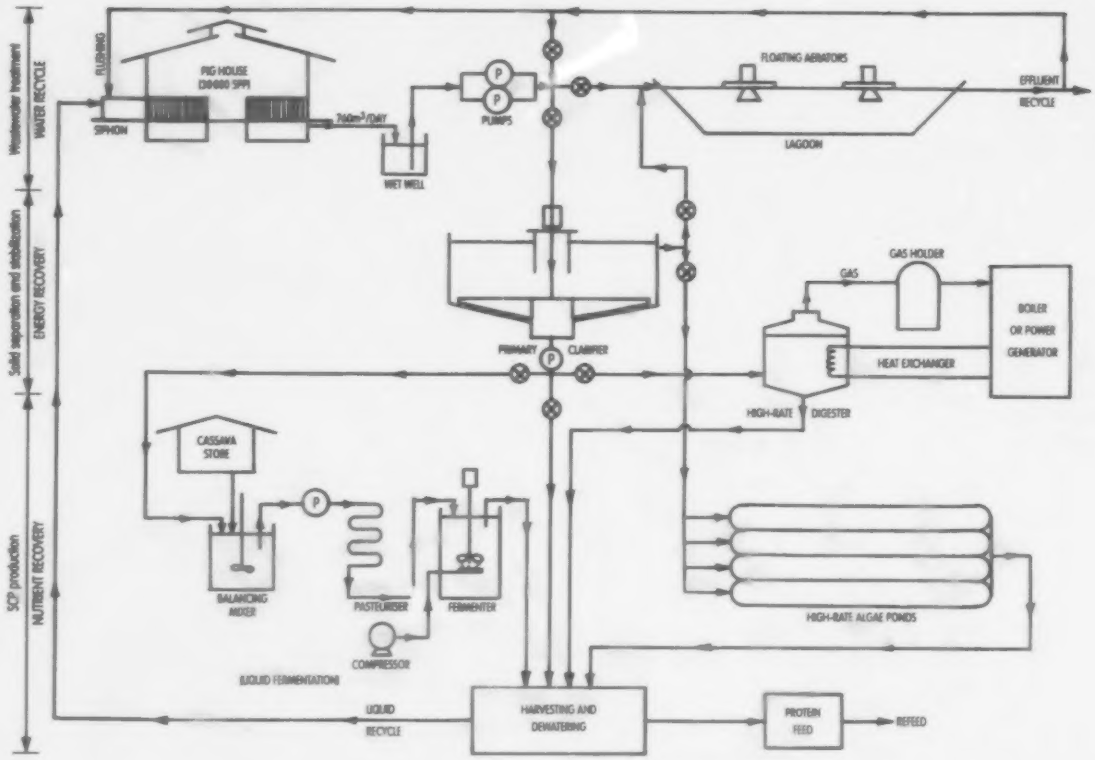
Wastewater treatment
WATER RECYCLE
Solid separation and stabilization
ENERGY RECOVERY
SCP production
NUTRIENT RECOVERY
FLUSHING
PIG HOUSE
(30 000 SPP)
SIPHON
760m³/DAY
WET WELL
P
P
PUMPS
FLOATING AERATORS
LAGOON
EFFLUENT
RECYCLE
PRIMARY
P
CLARIFIER
GAS
GAS HOLDER
BOILER
OR POWER
GENERATOR
HEAT EXCHANGER
HIGH-RATE
DIGESTER
CASSAVA
STORE
BALANCING
MIXER
P
PASTEURISER
FERMENTER
COMPRESSOR
(LIQUID FERMENTATION)
HIGH-RATE ALGAE PONDS
LIQUID
RECYCLE
HARVESTING AND
DEWATERING
PROTEIN
FEED
REFEED

Fig. 9.1. The original concept for a wastewater-treatment demonstration plant.

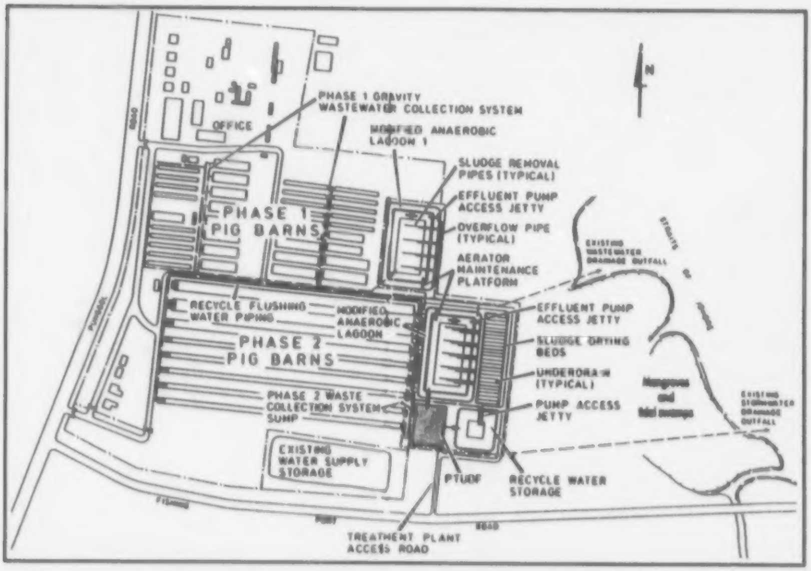
PHASE 1 GRAVITY WASTEWATER COLLECTION SYSTEM
MODIFIED ANAEROBIC LAGOON 1
OFFICE
SLUDGE REMOVAL PIPES (TYPICAL)
EFFLUENT PUMP ACCESS JETTY
OVERFLOW PIPE (TYPICAL)
AERATOR MAINTENANCE PLATFORM
PHASE 1 PIG BARNS
EXISTING WASTEWATER DRAINAGE OUTFALL
STRAITS OF
RECYCLE FLUSHING WATER PIPING
MODIFIED ANAEROBIC LAGOON
EFFLUENT PUMP ACCESS JETTY
PHASE 2 PIG BARNS
SLUDGE DRYING BEDS
UNDERDRAIN (TYPICAL)
Mangroves and tidal swamps
PHASE 2 WASTE COLLECTION SYSTEM SUMP
PUMP ACCESS JETTY
EXISTING STORMWATER DRAINAGE OUTFALL
EXISTING WATER SUPPLY STORAGE
PTUDF
RECYCLE WATER STORAGE
ROAD
PONGGOL
FISHING PORT ROAD
TREATMENT PLANT ACCESS ROAD
N

Fig. 9.2. Layout of the demonstration plant at IFPL (PTUDF, Pigwaste Treatment and Utilization Demonstration Facility).

Treatment Processes

The unit processes of PPP are shown in Fig. 9.3. These could be operated separately in three modules: solids stabilization treatment (SST), most practical treatment (MPT), or best demonstrated treatment (BDT).

SST, or primary treatment, consisted of a deep anaerobic lagoon, sand filter beds, and a sludge-composting area (Table 9.1). The effluent produced was to have a BOD_5 below 500 mg/L, (90% reduction). The solids would have to be stabilized until total volatile solids (TVS) of the resulting sludge was less than 70% of TTS (TVS/TTS < 70%). The TTS of the dried sludge to be disposed would have to be at least 20% (moisture content < 80%).

MPT was to be achieved by adding surface aerators to the lagoon, as well as a secondary sedimentation tank aided by chemical coagulants (Table 9.2). The effluent quality to be achieved was a BOD_5 of 250 mg/L plus solids stabilization as in SST.

BDT was designed to demonstrate unit operations that would reduce BOD_5 and TSS to less than 50 mg/L by the use of an oxidation ditch and recover energy while stabilizing the solids using a fully controlled anaerobic digester (Table 9.3).

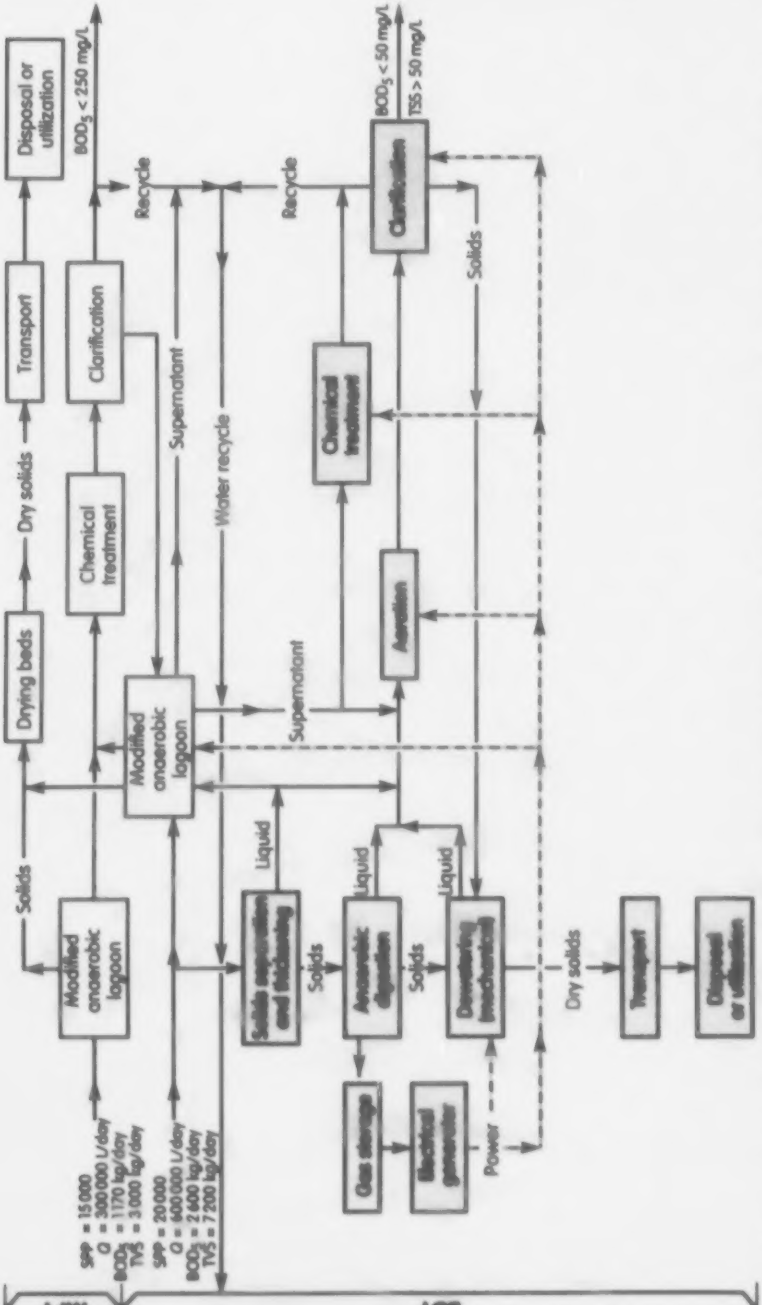
MPT
BDT
SPP = 15 000
Q = 300 000 L/day
BOD5 = 1170 kg/day
TVS = 3 000 kg/day
SPP = 20 000
Q = 600 000 L/day
BOD5 = 2 600 kg/day
TVS = 7 200 kg/day
Modified anaerobic lagoon
Solids
Drying beds
Dry solids
Transport
Disposal or utilization
Chemical treatment
Clarification
BOD5 < 250 mg/L
Recycle
Supernatant
Water recycle
Modified anaerobic lagoon
Liquid
Supernatant
Solids separation and thickening
Solids
Anaerobic digestion
Liquid
Solids
Dewatering (mechanical)
Liquid
Aeration
Chemical treatment
Clarification
Recycle
Solids
BOD5 < 50 mg/L
TSS > 50 mg/L
Dry solids
Transport
Disposal or utilization
Gas storage
Electrical generator
Power

Fig. 9.3. Unit operations for the most practical (MPT) and best demonstrated (BDT) treatment technologies at the Ponggol Pigwaste Plant: ▨, primary treatment; ☐, secondary treatment.

Table 9.1. Process design for solids stabilization treatment technology (SST).

Parameter[a]	Mean	Peak
Anaerobic lagoon		
Volume (m^3/SPP)	0.86	0.69
Total volume (m^3)	—	25000
Maximum depth (m)	5	5
HDT (days)	37	26
OLR (kg TVS/m^3 per day)	0.15	0.16
OLR (kg BOD/m^3 per day)	0.09	0.13
Sludge drying and composting		
Sludge drying beds	5	—
Total surface area (m^2)	3000	—
Capacity (m^2/SPP)	0.18	0.09
Dewatered sludge cake (TTS, %)	20	20
Dewatered sludge cake (TVS/TTS)	0.7	0.7
Composting area (m^2)	300	—

[a] See list of Acronyms and Abbreviations for definitions.

Resource Recovery

The second objective of PPP was to establish a full-scale treatment plant for pig waste that would integrate wastewater treatment with energy recovery and the recycling of water for flushing. When the treatment level was set at a level higher than SST, cash expenses for operation of the plant went up because energy was required to aerate the anaerobic lagoon. It was necessary, therefore, to add units that would recover some of the energy from the wastes to power the aerators. Moreover, in the Singapore experience, in which odour control was essential because of the proximity of residential areas, enclosed anaerobic digesters would serve the dual purpose of solids stabilization and energy recovery.

Once the water was treated, the only way to recover some of the costs of treatment was recycling. However, recycling required special design of the automatic flushing system of the barns so that the recycled water did not come into contact with either pigs or workers.

Training

The third objective was to provide hands-on research training for engineers and scientists and to train future operators in the use and maintenance of equipment and in the management of unit treatment processes. Because they are microbiological, these processes require husbandry to provide the expected level of treatment. The training program consisted of hands-on operations and small research projects for engineers and scientists. A private consulting engineering firm was also involved in developing the construction plans and assessing performance so that the experience would be shared by both the private and public sectors.

Table 9.2. Process design for the most practical treatment technology (MPT).

Parameter[a]	Mean	Peak
Aerators	8	10
Capacity (each) (kW)	5.5	5.5
Total capacity (kW)	44	55
Unit aeration capacity (W/m^3)	2.4	2.2
Unit aeration capacity, upper 1.5 m (W/m^3)	5.8	5.6
Unit aeration capacity, surface (W/m^2)	—	6.9
Unit aeration capacity (W/SPP)	2.9	2.8
Zone of influence (% lagoon surface)	200	210
Lagoon effluent pumps		
Capacity (L/s)	5.2	6.9
Rating (kW)	2.0	2.0
Sludge pump		
Capacity (L/s)	2.3–9.2	—
Rating (kW)	5.5	5.5
BOD_5 removal (%)	94	92
BOD_5 (mg/L)	250	1000
Sedimentation tanks		
Diameter (m)	5	—
Sidewater depth (m)	4	—
Scum scraper drive (kW/drive)	0.75	—
Flocculator drive (kW/drive)	0.75	—
HDT (h)	3.6	—
Alum dosing		
Mixing tanks (m^3/tank)	1.6	—
Mixer rating (kW/mixer)	0.5	—
Dosing pumps (L/s)	0.3–1.0	—
Peak overflow rate (m^3/m^2 per day	27	—
Maximum alum dose (mg/L)	500	—
Effluent concentration (TSS, mg/L)	250	—
Effluent concentration (BOD_5, mg/L)	250	—

[a] See list of Acronyms and Abbreviations for definitions.

Environmental and Economic Impact

The fourth objective was to use PPP facilities to assess the technical feasibility, economic costs, and environmental impact of the various levels of treatment and recycling operations because no other facility had been built on such a scale anywhere in the world.

Plant Design

The designing engineers were selected in February 1983 after a prequalification of three companies from the 26 firms that applied. The design was completed in April. Specifications and conditions for eight different

Table 9.3. Process design for the best demonstrated treatment technology (BDT).

Parameter[a]	Mean	Peak
Primary sedimentation		
Overflow rate (m^3/m^2 per day)	33	33
Weir loading (m^3/m per day)	41	41
HDT (h)	1.9	1.9
Peak solids flux rate (kg/m^2 per day)	380	400
TTS (mg/L)	14780	5200
TSS (mg/L)	12160	2580
TVS (mg/L)	11820	4050
BOD_5 (mg/L)	4260	2980
Biogas digester		
HDT (days)	15	—
OLR (kg TVS/m^3 per day)	2.9	—
Biogas production (m^3/day)	1930	—
Energy production (GJ/day)	39	—
Total sludge flow (m^3/day)	100	100
TTS (mg/L)	53100	33100
TSS (mg/L)	50500	32100
TVS (mg/L)	42900	23600
BOD_5 (mg/L)	9400	2800
TKN (mg/L)	2500	2500
Decanting centrifuge		
Solids loading rate (kg TSS/h)	540	—
Flow rate (at 3.2% TSS) (m^3/h)	20	—
Polymer dosing (kg/t TSS)	2	—
Suspended solids removal (%)	90	—
Cake (% TTS)	20	—
Cake (TVS/TTS, %)	70	—
Cake production rate (m^3/day)	12	—
Flow of centrate (m^3/day)	88	—
Aeration basin, oxidation ditch		
Volume (m^3)	250*2	—
OLR (kg BOD/m^3 per day)	0.40–0.60	—
Carbonation oxidation (kg BOD/kg VSS per day)	0.18–0.24	—
Nitrogenous oxidation (kg TKN/kg VSS per day)	0.13	—
Endogenous respiration (kg TAN/kg VSS per day)	0.05	—
Aerobic-anoxic process (kg TNN/kg VSS)	0.12	—
Effluent quality (mg BOD/L)	<250	<50
Recycle water storage		
Volume (m^3)	6600	—
Maximum water depth (m)	5	—
Recycle water pump capacity (L/s)	6.9	—

[a] See list of Acronyms and Abbreviations for definitions.

contracts were ready in August. International bidding was completed in December 1983 and construction began in March 1984. The plant was fully commissioned in May 1985. It was operated for research purposes until March 1988. In April 1988, it was given to the National University of Singapore for research and development in environmental engineering.

The consulting engineers produced reports that were evaluated and approved before proceeding with the next stage. The reports contained details of the investigations carried out, conceptualization of what was expected and how it was to be done, and detailed drawings and construction specifications. The following sections are brief summaries from the reports prepared by these consultants.

Predesign Studies

During predesign studies, the consulting engineers

- assembled and evaluated all available relevant information and reports and reviewed data on critical unit operations;
- reviewed existing waste collection and flushing facilities and carried out on-site tests to ensure that generated wastewaters would flow without interruption to the treatment plant site;
- prepared a comprehensive schedule of treatment plant wastewater flows and loadings;
- selected appropriate unit processes and prepared a detailed flow diagram for the treatment plant;
- established loading rates and effluent criteria for the unit processes and completed treatment process design computations;
- calculated sizes of treatment plant units and prepared an initial treatment plant layout;
- established a basis for estimating plant construction costs;
- estimated the construction cost of facilities included in the preliminary layout and modified initial proposals as required to suit the project budget;
- finalized the estimate of construction cost and prepared a schedule for project design and construction;
- developed proposals for construction and contracting procedures and the format of the bill of quantities; and
- prepared an engineering report containing all pertinent background data, a description of the predesign study, basic design criteria, cost estimates, outline drawings of proposed treatment facilities, and project schedule for final review and approval.

Industrial Farm Pte Ltd

Industrial Farm Pte Ltd (IFPL), for which the treatment plant was to be built, was a commercial farm that had been established in 1975 with a 30-year lease in the Ponggol PFA. The layout of the two phases of development of IFPL is shown in Fig. 9.2. In Phase I, the pig pens had slatted floors that allowed pig wastes to fall into collection pits under the floor. The wastes accumulated in the pits and underwent anaerobic decomposition for a number of days before overflow into concrete surface drains. The wastes were not fresh and, thus, could not be used for energy recovery.

In Phase II, the farm increased its capacity to 35 000 SPP in 1983 by building eight new barns in accordance with the specifications developed by the United Nations project (see Chapters 1 and 4). All eight pens were built with 1% floor slope to facilitate hydraulic flushing. Pig wastes accumulated in collection channels beneath slatted floors and were removed daily as a slurry with water. Water for flushing was supplied from tanks located at the west end of each barn. Water was released automatically from tanks when it reached a preset level. The raw wastewater was collected in a piped sewer system at the east end of the barns. The eight barns were the longest flushing barns in the world at the time of their construction.

The farm was of the closed-herd variety (see Chapter 2). Pig rearing began with breeding at the farm and continued to the production of porker pigs for slaughter. Porkers were marketed at 80–90 kg live weight, which was reached when they were 24–32 weeks old. The average live weight of all the pigs was estimated at 54 kg/SPP, which was the same as in other commercial farms in Singapore.

Climatic Conditions

Climatic conditions affect wastewater treatment processes. Temperature affects the rate of stabilization of wastewater by biological processes and rainfall affects treatment plant hydraulics and the drying of solids on open beds. Direction and strength of wind influence the diffusion of air into the water, the open air drying of solids, and aspects of plant layout associated with odour control. Long-term climatological records for Singapore were considered relevant to the design of wastewater treatment facilities (see Chapter 6).

Volumes of Wastewater

The design of wastewater treatment facilities was based on the estimated volume and composition of wastewater to be discharged from the barns. It was necessary, therefore, to determine characteristics of unit quantities of wastewater. Wastewater from the Phase II pig barns consisted of fresh pig waste, flushing water, pen washings, and leakage water. Storm water was collected separately and used for drinking and for washing pens. The wastes from Phase I of the farm were not fresh and were treated differently. Each of the tributary waste streams is described below.

Pig Waste

The available data and those collected on the site confirmed that the daily unit production of liquid pig waste was 4.5 L/SPP. Based on an average SPP for Phase II of 16 420, the estimated average flow into the collection sump was 74 m^3/day. The corresponding peak wastewater flow rate was 90 m^3/day for a maximum SSP of 20 000. Overflow from the barns in Phase I did not enter the sump but was conveyed directly into the lagoon. Only fresh wastes were collected for biogas digestion.

Flushing Water

Measurements were carried out at the Phase II facilities to determine the volume of water required to suspend and transport pig wastes to the end of the 283 m long barns. A minimum of 7 m^3 of water was required to achieve satisfactory scouring of each collection channel. An average design value of 10 m^3 of water per flush was adopted to allow for daily fluctuations in the quantity of solids accumulated in the waste-collection channels.

Discussions with farm management indicated that, initially, the pig barns would be flushed daily. However, the flushing frequency would be doubled when sufficient flushing water was made available from recycling. Based on the 20 flushing water tanks in Phase II, the average flushing flow was 200 m^3/day and the peak flow rate was 400 m^3/day.

Washing

Pig pens were washed regularly to remove solids from the pens, to clean the pigs, and to maintain a hygienic environment for the animals. The frequency of washing both pigs and pens varied with the type of pig: sows were washed daily, weaners and porkers every second day, and animals in the farrowing pens weekly. The volume of water required to wash a pig barn was based on two farm personnel hosing for 2 h/day at a rate of 4 m^3/h per hose. On this basis, 16 m^3 of water was required for each barn wash. For the desired frequency of barn washing, the total daily volume of water was calculated to be 66 m^3.

Leakage

Leakage water originated from drinking nipples installed in the pig pens. Pigs did not drink all the water flowing from the drinking tap and they often played with the tap to squirt water on themselves. A number of nipples leaked periodically while awaiting maintenance. These factors resulted in a continuous stream of drinking water entering the wastewater system. Flow measurements undertaken at one of the barns showed that the leakage volume was about 20 m^3/day. Hence, available data indicated that the flow of leakage water for the eight pig barns was about 160 m^3/day, or almost 10 L/SPP per day.

Summary

The average raw wastewater flow, based on an average SPP of 16 420 and one waste channel flush per day, was 500 m^3/day or an average unit wastewater volume of 30 L/SPP per day (Table 9.4). The peak raw wastewater flow, based on a peak SPP of 20 000 and two waste channel flushes per day was 720 m^3/day.

Table 9.4. Summary of design wastewater volumes.

Wastewater component	L/SPP per day	%	m^3/day	
			Average	Peak
Pigwaste	4.5	15	74	90
Flushing	12.2	40	200	400
Washing	4.0	13	66	70
Leakage	9.8	32	160	160
Total	30.5	100	500	720

Wastewater Characteristics

Pig waste included feces, urine, water, and pig hair, which formed solid balls of various sizes. The estimated average unit quantities of wastes emanating from Phase II pig farming operations are shown in Table 9.5. Studies to characterize the waste from Phase I pig barns showed a TTS in 24 samples ranging from 4 500 to 13 500 mg/L and averaging 8 000 mg/L. Associated TSS values ranged from 3 200 to 11 400 mg/L (average 5 800 mg/L) and TVS values, from 3 100 to 9 100 mg/L with an average of 4 200 mg/L.

Design Considerations

The design of the unit processes and operations within PPP were selected to meet the previously stated objectives, effluent criteria, and related considerations (such as budget constraints).

Design Life

The proposed PPP was to provide a full-scale demonstration and research capability and be suitable for future use as a permanent

Table 9.5. Design parameters and daily loadings of pig waste constituents.[a]

Constituent[b]	kg/SPP per day	Loading (kg/day)		Average concentration (mg/L)
		Average	Peak	
TTS	0.45	7390	9000	14780
TSS	0.37	6080	7400	12160
TVS	0.36	5910	7200	11820
VSS	0.30	4930	6000	9860
TDS	0.08	1310	1600	2620
BOD_5	0.13	2130	2600	4260
TKN	0.030	493	600	986
TAN	0.015	264	300	492
TPP	0.004	72	88	143

[a] The loading rates were the wastewater stream of Phase II, which averaged 500 m^3/day with a peak of 720 m^3/day. The average design was 16 400 SPP and the peak was 20 000 SPP.

[b] See list of Acronyms and Abbreviations for definitions.

treatment plant by IFPL, which had been given a lease until 1995. The works, therefore, were to be constructed to normal wastewater treatment plant standards and a design life of 15 years was adopted for the design and economic analyses.

Effluent Standards

The treatment plant was designed to produce an effluent that met the standards described in Table 1.2: BOD_5 consistently less than 250 mg/L for an average SPP of 31 000 and a peak SPP of 35 000.

Selected unit processes were designed to achieve a higher standard of treatment to demonstrate the operational and cost implications of possible future reduction of BOD_5 and suspended solids to 50 mg/L and removal of nitrogen from the wastewater. The associated wastewater treatment units were sized for 63% of the total wastewater flow from the average SPP of 31 000 for increased BOD_5 and suspended solids removal and 12% of the total average wastewater flow for nitrogen removal. These constraints in treatment capacities were based on budgetary constraints.

Solids Treatment

The primary objective of solids treatment was to produce a sludge that could be disposed on land without creating a nuisance. A secondary objective was to maximize the removal of solids from the wastewater to prolong the life of the anaerobic lagoon treatment units. Solids treatment design criteria included reduction of the total volatile solids (TVS) present in the raw sludge by not less than 45% and dewatering of the stabilized solids to a concentration of not less than 20%.

Because there was some decomposition of the solids in the pits under the slatted floors in Phase I, the pit effluent was discharged without sedimentation into the anaerobic lagoon. Primary solids separation facilities were designed for a peak SPP of 20 000 in Phase II. Mechanical dewatering equipment was designed for dewatering solids withdrawn from the anaerobic lagoon by extending the normal hours of operation beyond 1700, if necessary.

Resource Conservation

To demonstrate potentially beneficial water and energy conservation techniques, biogas was recovered from sludge-treatment units and treated wastewater was reused to flush the 20 waste channels in the barns.

Reliability and Flexibility

Reliability was sought through duplicate units wherever feasible, robust equipment that was simple to operate and maintain, appropriate working conditions for plant staff, and a comprehensive system of overflows and bypasses. Flexibility of operation resulted from the duplicate equipment and bypasses.

Ease and Economy of Operation

The working environment at the plant was enhanced by providing adequate space and related facilities for maintenance; convenient storage for tools, spare parts, and consumables; safe working conditions; adequate lighting and ventilation; and appropriate amenities such as air-conditioned offices with refrigerators, kitchen sinks, changing rooms, and toilets, and landscaped surroundings.

Esthetic Considerations
Odour from waste treatment was controlled so as not to increase the level of odour normally associated with pig farming, and mechanical noise was limited to residential standards appropriate to the area. Because the wastes were collected under slatted floors and flushed daily, odour-generating surfaces were minimized.

Facilities Design

The treatment processes and unit operations of the three treatment modules (SST, MPT, BDT) are shown schematically in Fig. 9.3. The parameter values and sizes of the facilities as designed are given in Tables 9.1 for SST, 9.2 for MPT, and 9.3 for BDT. Considerations and formulae in the design of the major unit operations are briefly highlighted in the following sections.

Waste Collection and Diversion
Flushed wastewaters from the pig barns were collected in an underground interceptor drain that conveyed them to an open channel. The channel was equipped with a sluice gate to allow the waste stream to go into the pump well or into the lagoon. Overflow pipework was provided in the sump itself to discharge raw wastewater to the adjacent anaerobic lagoon in the event of pump failure.

A 20-mm screen was placed in the sump entrance to keep twigs and plastic vaccine bottles from entering the sump. The 4 m diameter, 5 m deep circular concrete pump well had a 45° hopper bottom to prevent the accumulation of solids. Its storage capacity was 20 m^3 below the invert level of the lowest incoming sewer. This meant that only two flushings of 10 m^3 each could be handled at once. Therefore, the 20 automatic flushing tanks had to be managed so that no two tanks flushed at the same time. A program was worked out with farm management to accomplish this objective.

The raw wastewater pump station was equipped with two 8.7-L/s, low-speed, progressive cavity pumps fitted with 5.5-kW drive units. One pump had a capacity for the maximum raw wastewater flow rate; the second unit was a standby. A simple roofed structure was constructed over the pumping equipment and pump well to protect the equipment and shelter the operator from heavy rainfall and the hot tropical sun.

The raw wastewater pumps were automatically controlled by level switches installed in the collection sump. Normal operating water levels in the sump were maintained below the invert level of the inlet penstock. If a number of pig barns were flushed simultaneously, the rate of inflow to the collection sump could exceed the capacity of the raw wastewater pump and raise the water level. Therefore, an additional high-level float switch was installed to stop the recycle water supply pump and prevent operation of additional flushing units if a high water level existed in the raw wastewater pump well.

Primary Sedimentation

Separation of solids from the raw wastewater took place in a 5 m diameter, 3 m deep circular primary sedimentation tank. Raw wastewaters or lagoon effluent were pumped from the pump well to a 1.2 m diameter steel inlet distribution well in the centre of the sedimentation tank. The sedimentation tank was designed for a peak overflow rate of 33 m^3/m^2 per day, an HDT of 1.9 h, and a solids flux rate of 380 kg/m^2 per day (see Table 9.3).

Effluent was discharged over a circumferential collection launder. The effluent launder was fitted with a single V-notched overflow weir, discharged by gravity, and could be directed either to the oxidation basins or the anaerobic lagoon. Settled solids were scraped to a central sludge hopper before they were pumped to treatment facilities such as the digester tank or the lagoon. The tank floor sloped at a gradient of 1 in 12 to a central, 0.8 m deep sludge hopper. The primary sedimentation tank was equipped with rotating scum-removal equipment to prevent accumulation of floating solids on the surface. Scum was discharged with the effluent to the anaerobic lagoon.

Anaerobic Sludge Digestion

Raw sludge was pumped continuously during the day from the primary sedimentation tank to the anaerobic sludge digester. The sludge digester was covered, heated, and mixed to achieve the conditions required for stable operation of the high-rate mesophilic digestion process. Compressed gas mixing equipment was installed in the digester to ensure that relatively inert material included in the pig feed did not accumulate in the digester and to control the formation of scum under the digester cover. Gas produced as a by-product of anaerobic sludge digestion was used to fuel the sludge heating equipment.

Two progressive-cavity, low-speed, variable-speed raw sludge pumps, each with a capacity of 2.4 L/s and a 4-kW electric motor, were installed. The pumps discharged raw sludge from the primary sedimentation tank to the anaerobic sludge digester. Each raw sludge pump had a capacity for normal operating requirements; the second unit was a backup. One pump was operated manually as continuously as possible to avoid anaerobic decomposition of sludge in the hopper of the primary sedimentation tank and to prevent sludge rising to the surface of the tank.

Anaerobic digestion of the raw sludge was carried out in a 16.5 m diameter circular concrete sludge digester with a side water depth of 7 m. The digester had an effective operating volume of 1 500 m^3 and provided 15 days detention for the raw sludge. The concrete floor of the digester sloped at a gradient of 1 in 4 to a central digested sludge withdrawal point. The design OLR was 2.9 kg TVS/m^3 per day.

The digester was fitted with a steel cover equipped with a central gas-collection dome. The cover floated on the surface of the digester contents and moved up and down depending on the quantity of sludge in the digester. A sludge overflow pipe was provided to ensure that the digester was not accidentally overfilled. All steelwork associated with the digester cover was sandblasted and painted with a high-quality epoxy paint to prevent corrosion.

The contents of the digester were vigorously mixed by a compressed digester-gas system of high-intensity spargers inserted through the floating cover. Two liquid-ring gas compressors were installed under a suitable cover on the digester roof to supply compressed gas through a rotary valve to each sparger in turn. Each gas compressor supplied 50 L/s of compressed gas at a pressure of 70 kPa and was fitted with a 7.5-kW motor. The gas compressors were time controlled and operated as duty and standby units. All electrical equipment associated with the gas-compression and mixing system was designed to suit the appropriate level of hazard caused by the presence of combustible digester gas.

A dual-fuel (gas or oil), hot water boiler was installed to heat the raw sludge entering the digester and maintain the digester contents at the mesophilic operating temperature of 35°C. The hot water boiler and the water-to-sludge heat exchanger were installed as an integrated unit outside the sludge digester. A 9.2-L/s, progressive-cavity, low-speed sludge-recirculation pump fitted with a 5.5-kW motor circulated the digesting sludge through the heat-exchanger tubes. The sludge-recirculation pump, heat exchanger, and associated pipes were fitted with adequate access openings and flushing points to facilitate clearing of blockages caused by solids in the circulating sludge.

Anaerobic digestion of the raw sludge was projected to reduce the TVS content from 81 to 70% of TTS and to produce stabilized material suitable for efficient mechanical dewatering and subsequent disposal on land without the creation of odour or insect problems.

Sludge Dewatering

Extensive pilot plant studies undertaken by the project team indicated that sludge dewatering by centrifuge was preferable to alternative mechanical dewatering systems. Centrifuge dewatering systems had a lower initial capital cost and required less operator attention. A well-operated centrifuge produced a sludge cake containing 25% TTS that was suitable for transport by truck for land disposal.

Digested sludge was pumped by a low-speed, variable-speed, progressive-cavity pump from the bottom of the anaerobic sludge digester to the sludge-dewatering equipment. Sludge pipework was provided so that the digested sludge pump could be used as a standby unit for the sludge-recirculation pump if required.

The sludge-dewatering equipment consisted of a solid bowl decanter centrifuge fitted with a concurrent scroll to continuously remove dewatered sludge. The centrifuge was driven at a maximum speed of 1 800 rpm by an 18-kW electric motor. Wearing surfaces of the scroll and sludge outlet were finished with tungsten carbide to minimize wear and extend the time between major overhauls.

The sludge-dewatering centrifuge was installed on an elevated structural steel platform; therefore, the dewatered sludge cake fell by gravity into sludge transport vehicles, and the centrate flowed by gravity to the aerobic biological treatment units. A suitable monorail and hoist were provided for the installation and maintenance of the larger items of equipment included in the sludge-dewatering system.

A polyelectrolyte storage, batch mixing, and dosing system was installed adjacent to the centrifuge to supply coagulant to the digested sludge before it was centrifuged. The polyelectrolyte solution was introduced at the inlet to the sludge-distribution pipework. The polyelectrolyte system consisted of a chemical storage area, a stirred batch mixing tank, a polyelectrolyte aging tank, and chemical solution metering pumps. To prepare a batch of polyelectrolyte solution, the batch tank was filled with water from the plant water supply system and the necessary amount of chemical was added manually. After the polyelectrolyte was added, the contents of the batch tank were mixed with a slow-speed paddle stirrer and the solution was transferred to the aging tank.

The chemical metering pumps were of the positive displacement type and had variable-speed drives and variable-stroke plungers. The chemical pumping rate could be selected manually by varying pump speed and stroke. The pumps were started manually and stopped automatically when the centrifuge was stopped. The type of polyelectrolyte and the dose needed for the required degree of solids capture and cake dryness were based on the results of a series of trials made after the plant was commissioned.

The mechanical sludge-dewatering system was projected to remove up to 90% TSS present in the anaerobically digested sludge and produce a dewatered sludge cake containing not less than 20% TTS. The centrate discharged from the system was expected to have a BOD_5 of approximately 2 270 mg/L and, thus, had to be returned to the plant for treatment. Table 9.3 gives the major design capabilities of the decanting centrifuge and its projected performance.

Sludge-Drying Beds

Five sludge-drying beds were constructed to dewater the stabilized sludge that was removed from the anaerobic lagoon or the digester. Each drying bed had a surface area of 600 m^2; therefore, a total area of 3 000 m^2 was available for sludge dewatering (see Table 9.1). The sludge-drying area had a capacity to dewater solid wastes from 20 000 SPP.

The beds, which were 40 cm thick, were constructed with a 10 cm thick crushed stone base, a 15-cm intermediate crushed stone layer, and a 15-cm sand layer. Drainage tiles were provided at appropriate locations to convey underdrainage water by gravity to the anaerobic lagoon. Drainage tiles were constructed from 15 cm diameter UPVC slotted pipe. Each drying bed was surrounded by a 50 cm high concrete wall to retain a 45-cm layer of wet sludge. Access for sludge-removal equipment was provided by concrete ramps and steel-beam wheel tracks. A skid steer type tractor loader was used to remove dried sludge from the beds.

Anaerobic Lagoon

An anaerobic lagoon was constructed to treat settled wastewater. The lagoon had a volume of 25 000 m^3 and a maximum water depth of 5 m (see Table 9.1). The lagoon had internal slopes of 2 to 1 at the top and 3 to 1 at the bottom of embankments. The top slope was surfaced with concrete to prevent erosion from the wave action caused by the surface aerators and the wind. A minimum freeboard of 1 m was provided.

The raw wastewater was discharged to the lagoon through a submerged inlet pipe to minimize the release of odours. An overflow weir was installed to discharge treated wastewater to an effluent outfall drain. The lagoon outlet was equipped with flap gates to prevent backflow at times of high tide, and scum baffles were fitted to prevent discharge of floating material over the outlet weir.

Stopboards were used to raise the water level and prevent overflow when the effluent was being pumped to the oxidation ditch for further treatment. It was envisaged that the level of the lagoon would normally be maintained within 50 cm above or below the nominal top water level. The storage volume available within this operating range was adequate to attenuate variations in flow rate caused by rainfall and by normal changes in pig population.

The lagoon was equipped with 10 high-speed, direct-drive, mechanical surface aerators driven by 5.5-kW electric motors. The aerators were installed with shallow submergence to promote aeration of the top layer of liquid in the lagoon without excessive disturbance of the digesting solids below. A platform was provided to facilitate maintenance of the aerators, and the aeration equipment could be removed from the lagoon using a mobile crane.

Fifteen fixed, 10 cm diameter, sludge-removal pipelines were installed in the lagoon (Fig. 9.4). The sludge-removal pipes had quick couplers so they could be readily connected to a portable sludge pump using flexible hose. The sludge pump discharged into a fixed, sludge-discharge piping system using similar quick couplers and flexible hose. The sludge pump was a low-speed, progressive-cavity unit capable of delivering up to 9.2 L/s of sludge to the sludge-drying beds or the sludge-dewatering centrifuge. The pump was driven by a 5.5-kW electric motor through a mechanical variable-speed drive with a minimum speed range of 3 to 1. Electrical outlets were located adjacent to each pump connection in the sludge removal and discharge network. The sludge pump, electric motor, variable-speed drive unit, hoses, and extension cord were conveniently mounted on a rubber-tire trailer.

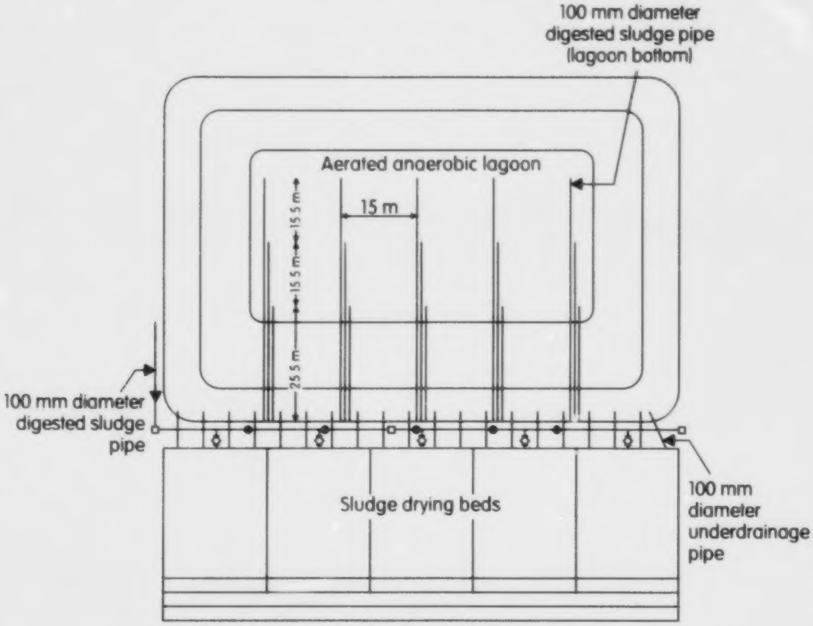
100 mm diameter
digested sludge pipe
(lagoon bottom)
Aerated anaerobic lagoon
15 m
15.5 m
15.5 m
25.5 m
100 mm diameter
digested sludge
pipe
Sludge drying beds
100 mm
diameter
underdrainage
pipe

Fig. 9.4. Pipe and pump network designed for desludging the aerated anaerobic lagoon.

Each sludge-removal pipe was designed to remove accumulated sludge from an equivalent lagoon floor area of 14 m by 14 m. Optimum operation of the sludge-removal system was achieved by frequent variation of the location selected for sludge removal. Before the sludge was pumped from a given location, the nearby contents of the lagoon were gently fluidized by pumping a small quantity of sludge from an adjacent area into the sludge-withdrawal pipe.

The lagoon effluent pump was a fixed-speed submersible centrifugal pump capable of delivering 6.9 L/s of effluent to the secondary sedimentation tanks. The pump was driven by a 2.0-kW electric motor. Treatment in the aerated anaerobic lagoon reduced the TVS present in the sludge to not more than 70% TTS and reduced the BOD_5 of the effluent to less than 250 mg/L most of the time. Further treatment of the effluent by chemical addition and secondary sedimentation was designed to ensure that the environmental control standards were satisfied at all times.

Aerobic Biological Treatment

The activated sludge aeration basins and associated aeration equipment were designed to achieve oxidation of both carbonaceous and nitrogenous substances in the wastewater. The aeration basin also provided a sufficient volume to enable an anoxic zone to be established within the tank for partial denitrification of the fully nitrified wastewater. The denitrification facility was designed to demonstrate the feasibility of nitrogen removal by biological treatment. The percentage of solids present in the wastewater from the sludge-dewatering centrifuge could be adjusted by varying the polyelectrolyte dose and the centrifuge operating parameters. This variation of the BOD_5 to nitrogen concentration ratio in the influent to the aerobic biological treatment process allowed control of the rate of denitrification.

Pipes were also installed to enable the operator to pump settled wastewater from the anaerobic lagoon for further aerobic treatment. Hydraulic capacity was provided to treat the total wastewater flow from the peak Phase II population of 20 000 SPP, and the aeration equipment was adequate to oxidize the carbonaceous material in the waste under maximum flow conditions. The active biological solids were separated from the contents of the aeration basins and returned to the tank inlets through circular secondary sedimentation tanks.

Aerobic biological treatment of wastewater took place in two 2.5 m deep concrete oxidation ditches. Each oxidation ditch was 5.0 m wide and 21 m long and had a liquid volume capacity of 250 m^3 (see Table 9.3). The two oxidation ditches were constructed with a common dividing concrete wall and non-load-bearing, central flow retaining walls. Each oxidation ditch was equipped with two horizontal shaft mechanical aerators driven by 15-kW electric motors. The aerators circulated and mixed the contents of the ditch to prevent settlement of solids and to provide the oxygen required for aerobic biological treatment. The aeration basins were designed with an OLR of 0.4–0.6 kg BOD/m^3 per day (Table 9.3).

The oxidation ditches were fitted with adjustable overflow weirs to vary the depth of submergence of the aerators and, consequently, the rate of oxygen transfer from the atmosphere. The rate of aeration and the characteristics of the wastewater discharged to the oxidation ditches were controlled to create an anoxic zone in one or both ditches to demonstrate the denitrification process. The installed aerobic biological treatment system had a capacity to treat up to 448 m^3 of wastewater per day from the anaerobic lagoon and to reduce the influent BOD_5 by 95% (from 620 to 30 mg/L). In this mode of operation, little if any oxidation of nitrogen would occur, and removal of nitrogen by denitrification would not occur.

Chemical Treatment and Secondary Sedimentation

The contents of the aeration basins were discharged continuously to secondary sedimentation tanks for further treatment by chemical addition and sedimentation. Alum was added to the central flocculation zone of the sedimentation tanks to coagulate the solids and improve the performance of the sedimentation process. Settled solids were pumped back to the aeration basins. Effluent from the sedimentation tanks overflowed into circular launders for discharge by gravity either to the recycled water pond or to the plant effluent discharge drain.

The flocculation zone of the secondary sedimentation tanks was equipped with slow-speed mixing, sludge-scraping, and surface-skimming equipment. Scum collected from the surface of the secondary sedimentation tanks was discharged to the anaerobic lagoon, and excess solids produced in the oxidation ditches were pumped to the sludge-dewatering equipment or the anaerobic lagoon.

The floor of the clarifiers sloped at a gradient of 1 in 12 to a central 0.5 m deep sludge hopper. Mixed liquid from the oxidation ditches, or lagoon effluent, was discharged to a steel central flocculation and inlet distribution well that provided 9 min of detention time at average flow conditions. The inlet well was equipped with a slow-speed flocculation paddle mixer driven by a 0.75-kW electric motor. Settled wastewater overflowed from the clarifiers at a rate of 18–30 m^3/m^2 per day into a circumferential, double-sided effluent-collection launder fitted with V-notched overflow weirs.

The secondary sedimentation tanks were equipped with a 0.75-kW, centre-drive, rotating sludge-collection mechanism and associated surface-skimming equipment. Settled sludge that collected in the sludge hopper was removed by two 2.8-L/s, low-speed, variable-speed, progressive-cavity sludge-return pumps driven by 3.0-kW electric motors.

An alum storage, batch mixing, and chemical dosing system provided chemical treatment to the outflow from the anaerobic lagoon before clarification. The coagulant chemical treatment system could also improve the settleability of the activated sludge if necessary. The alum chemical system was integrated with the similar facilities for the storage and dosing of polyelectrolyte, and was located in the plant equipment building. The alum chemical system consisted of an area for the storage of bagged chemicals, a bag splitter, two stirred solution tanks, and alum solution metering pumps. Unloading and bag-handling equipment was installed in the chemical storage area and was also used as part of the polyelectrolyte system.

Alum was batch mixed in solution tanks supplied with water from the plant supply system. Chemical metering pumps were positive-displacement, variable-speed, variable-stroke pumps similar to those in the polyelectrolyte system. The pumps were started manually and stopped automatically when the appropriate wastewater supply pump was stopped.

Chemical treatment and clarification of wastewater from the anaerobic lagoons reduced the BOD_5 of the influent by 75% (from up to 1 000 mg/L to less than 250 mg/L, depending on the quantity of alum added).

Digester Gas Utilization

Digester gas contained approximately 65% methane and 35% carbon dioxide and was produced at an average rate of 1 500 m^3/day in the anaerobic sludge-digestion process. Surplus gas not required as fuel to heat the digester was used to operate a naturally aspirated generator. Electricity from the generator was used to operate the lagoon aerators. An automatic audible alarm was installed to indicate failure of the gas supply when the generator was in operation.

Engine-cooling water was circulated through a 60-kW heat exchanger installed in the digester hot water heating circuit. The operation of the hot water boiler was automatically controlled by thermostats that maintained a constant temperature in the water jacket of the sludge heat exchanger.

The gas system was fitted with antivacuum and pressure-relief valves, flame arresters, condensate and drip traps, gas meters, and a waste-gas burner to ensure continuous availability of a safe, complete, and operable system. A separate pilot light system, supplied with bottled liquid petroleum gas, was installed to maintain continuous operation of gas-burning equipment.

Building Works

Building works consisted of an equipment and chemical storage building and an operator amenity and sample preparation building. The equipment building had a concrete floor and equipment foundations constructed at ground level, half-height masonry walls topped with open steel mesh, and a timber-framed roof covered with an insulated sheet steel roofing system. The open steel mesh upper walls provided the ventilation and freedom of air movement required for the satisfactory continuous operation of mechanical equipment and ensured acceptable working conditions for plant staff. Minimal partitioning was required, except to provide a relatively dust-free area for installation of electrical switch gear and motor-control equipment.

All equipment was installed on raised plinths and a comprehensive system of floor drains was provided to facilitate washing and encourage good housekeeping. Appropriate levels of lighting were provided to ensure safe and efficient working conditions, and adequate stormwater disposal facilities were installed to prevent rainwater damage or flooding.

The operations building was of masonry construction and was built on a ground-level concrete floor. It had a timber-framed insulated sheet steel roof. A number of glass louvred windows were installed to ensure adequate ventilation, and the sample preparation room and associated office area were air conditioned. The building included basic amenities such as a lunch room, toilets, office desk, chair, filing cabinets, and a sample-preparation room fitted with a refrigerator, sink, and laboratory benches. There was also an area to display charts, diagrams, and pictures for visitors.

Building services for light and power, fire protection, hot and cold water, and stormwater and waste drainage systems were provided in accordance with government regulations.

Recycled Water System

The recycled water storage lagoon had an operating capacity of 6 600 m^3, which represented 30 days' storage at the estimated average use of 200 m^3/day for flushing the Phase II pig barns. The lagoon had a maximum water depth of 5 m and was constructed with earth embankments with 3 to 1 side slopes. Concrete lining to prevent erosion was not required.

Water was discharged by gravity to the storage lagoon from the secondary sedimentation tanks. A pump and associated 80 mm diameter pipework supplied treated wastewater from the storage lagoon to the pig barns for waste flushing.

The water pump was a fixed-speed, open-impeller, centrifugal submersible pump identical to units installed in the anaerobic lagoon outlet. The pump had a capacity of 6.9 L/s, was driven by a 2.0-kW electric motor, and was mounted on fixed guides.

Electricity Supply and Plant Control

Because the total connected load amounted to approximately 150 kW, it was necessary to install a new substation to supply electricity to the plant. Mains supply switch gear, electricity meters, distribution boards, and motor control centres were located in the equipment building. Power supply and control cables were primarily reticulated on pipe racks and cable trays to facilitate access for maintenance and to minimize underground installation and associated costly site works.

Construction Contracts

The construction of the Ponggol Pigwaste Plant was based on detailed drawings and written specifications that were tendered internationally. In total, there were 10 separate contracts: 2 for engineering services, 2 for construction contractors, and 6 for the supply of equipment

Engineering Contract

The engineering contract was awarded to an Australian firm. They were to prepare a preliminary report that detailed the approach to be taken and outlined the design. Once the preliminary report was approved, the engineers prepared construction drawings, specifications, and other contract documents; determined quantities of materials and services; and estimated construction costs. A second contract covered general supervision and engineering services during construction, and supervision of start-up operations of the treatment plant.

Construction Contract

The construction contract was awarded to a Singapore firm. The contract was a fixed lump-sum amount for construction of the works and installation of the equipment. The works were to be completed in accordance with the schedule and any delays would result in money being withheld from the contractor. The contractor received an initial amount followed by monthly payments up to a specified percentage of the total, which was due on completion of all aspects of the work.

Mechanical Contracts

The major mechanical contracts for specialized wastewater treatment equipment were awarded to Australian firms. The performance specifications for the equipment were prepared by the consulting engineers. The manufacturers had to design, fabricate, and assemble the equipment to meet the specifications.

Bill of Quantities

Although the contracts for the construction of the treatment plant were awarded on a fixed lump-sum basis, the contractors were required to complete a bill of quantities. These were used to calculate monthly progress payments to the contractor, determine the method of expenditure of provisional sums, and guide evaluations of the cost of variations to the contract. The bill of quantities and unit prices were used to calculate costs of unit operations in the plant.

Construction Costs

Construction costs are presented in terms of the five major contract components in Fig. 9.5. Initial capital costs amounted to 61 USD/SPP, based on a maximum SPP of 35 000. The total costs for the plant amounted to 2 million USD.

Engineering

Engineering surveys, design, and construction management accounted for 13.4% of the total demonstration plant cost (Fig. 9.5), which included

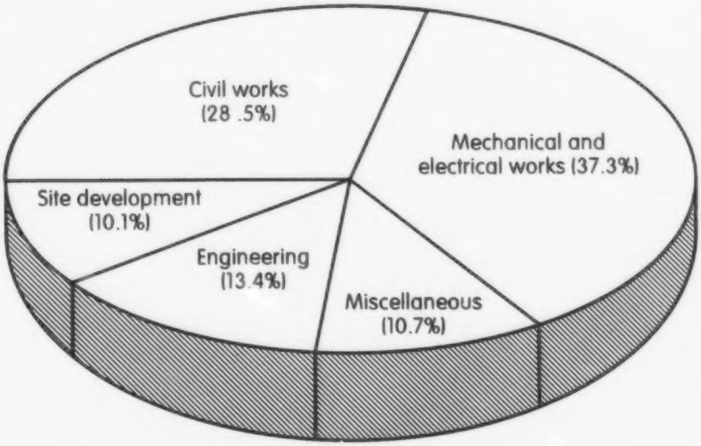

Fig. 9.5. Five major cost components of PPP construction.

several trips by the Australian consultants to Singapore. This percentage for engineering services falls within the average range for plants of this complexity. The engineering costs would have been higher if the consulting engineers had had to research suitable treatment processes and recommend a system. However, after reviewing the preliminary design that had been developed, the engineers accepted the overall concept and agreed with the sizing of the unit operations. The cost for engineering surveys and design was about 7.54 USD/SPP.

Site Development

Site clearance, earthworks, and piling amounted to 6.20 USD/SPP or 10.1% of the total initial cost (Fig. 9.5). The land was a swampy area that had to be drained and cleared of mangrove vegetation and trees. Forty-five piles were set at depths of 28 to 40 m. Except for the anaerobic lagoon, which was 6 m deep, the other earthworks were minor. Excavated soil was used within the site to fill swampy areas; some was piled in mounds.

Civil Works

The cost of civil works amounted to 17.41 USD/SPP, or 28.5% of the initial costs (Fig. 9.5). The structures were of sufficient strength and quality to meet the Singapore building code requirements and all relevant international standards. As such, the facilities were more expensive than conventional farm buildings.

Mechanical and Electrical Works

The cost of mechanical equipment plus electrical substation equipment and instrumentation amounted to 23.20 USD/SPP, which was 37.3% of the initial capital costs.

Contractor Services

The initial payment to the construction contractor amounted to 4.80 USD/SPP (8% of the initial costs). This money was given to the contractors to establish a site office, pay insurance and bond premiums, bring earth-moving equipment to the site, begin hiring workers, and purchase essential materials to initiate construction.

Cost of Unit Facilities

Table 9.6 gives the costs of the eight major unit facilities or unit operations that made up PPP. The costs were calculated by multiplying the quantity of materials used for each unit by the unit costs given by the

Table 9.6. Initial capital costs (ICC) of unit operations at PPP.

Unit operation	Total volume (m^3)	Liquid volume (m^3)	Cost of materials (USD)	Overhead (USD)	Total cost		
					USD	% ICC	USD/SPP[a]
Raw wastewater pump station	34	33	35795	44866	80661	4	2.30
Primary sedimentation tank	68	62	45964	59729	105693	5	3.02
Anaerobic sludge digestion	1868	1612	423312	534504	957816	45	27.37
Oxidation ditches	548	510	107954	137396	245350	11	7.01
Secondary sedimentation tank	87	81	46693	59428	106121	5	3.03
Aerated anaerobic lagoon	33456	29112	143846	171602	315448	15	9.01
Sludge drying beds	2890	2752	133114	169417	302531	14	8.64
Recycle water pond	7600	6600	11475	14604	26080	1	0.76
Total			952873	1188667	2139540	100	61.14

[a] Based on maximum SPP of 35 000.

contractors. Engineering and contractor services were added as overhead cost.

A new bill of quantities was developed from the detailed construction drawings after the facilities were built. Materials costs were based on unit costs given in the bid of the winning contractor, and were checked with current prices at the time of construction (1984–1985). The cost of materials was subtracted from the total contracted cost for each unit operation. The difference was considered overhead. Overhead amounted to 55.6% of construction cost and was added at that percentage to the cost of each unit facility.

Operating Costs

Operating costs consisted of four components: utilities (54.4%), maintenance of mechanical equipment (4.4%), labour (32.0%), and miscellaneous (9.1%). Utilities were further broken down to electricity, water, chemicals, and fuel. Table 9.7 details the annual operating costs (AOC) of the unit operations.

Electricity

Power was determined from the measured current input to each motor, the voltage, and the power factor given in the manufacturer's literature. The running hours of each piece of equipment, (recorded in the control panels) were used to calculate power consumption. Calculated power consumption was counter-checked with the recorded meter reading for the whole plant. The power cost was based on an average rate of 0.09 USD/kWh. Electricity costs amounted to 47.8% of the total AOC.

Water

The digester gas recirculation compressor unit used 28 m^3/day of water as a sealant. Water was also used in the chemical treatment unit. Both these uses required clean public water that cost 0.72 USD/m^3. Equipment was washed with recycled water, and thus is not included in the operating costs. Water cost 5.0% of the total AOC.

Chemicals and Fuel

Approximately 40 kg of alum was used daily as a coagulant in the secondary sedimentation tank when it was run continuously. Alum cost 0.15 USD/kg. The loader used to remove dried sludge from the sand filter beds and the truck used to transport the sludge within 1 km to surrounding areas consumed about 50 L of diesel fuel per month. Fuel costs were 0.28 USD/L. Chemical and fuel costs were 1.6% of the total AOC.

Table 9.7. Annual operating costs (AOC) of the unit operations in the PPP.[a]

Unit operation	Utilities				Mechanical equipment	Labour	10% misc.	AOC	
	Electricity	Water	Chemical	Fuel				Total	%
Raw wastewater pump station	1076	0	0	0	3973	7233	1228	13510	8.8
Primary sedimentation tank	1169	0	0	0	2035	7365	1057	11626	7.5
Anaerobic sludge digestion	8093	7207	0	102	206	6806	2241	24655	16.0
Oxidation ditches	25229	0	0	0	136	5079	3044	33488	21.7
Secondary sedimentation tanks	4094	522	2160	0	45	6791	1361	14973	9.7
Aerated anaerobic lagoon	33779	0	0	0	361	5688	3983	43811	28.4
Recycle water storage pond	211	0	0	0	21	4542	477	5251	3.4
Sludge drying bed	0	0	0	168	66	5843	608	6685	4.3
Total	73651	7729	2160	270	6843	49347	13999	153999	100
% of total AOC	47.8	5.0	1.4	0.2	4.4	32.0	9.1	100	—
AOC using biogas	39873	7729	2160	270	6843	49347	10017	116243	—

[a] All costs are expressed in US dollars. The total AOC were based on a minimum average SPP of 16 500 and maximum of 35 000, which at an annual extraction rate of 1.6 gave the corresponding porkers marketed per year (PMY) of 26 400 and 56 000. The labour costs are from Table 9.8.

[b] Use of biogas saved on electrical charges for the floating aerators.

Mechanical Equipment

Routine or preventive maintenance of equipment included oil changes (at 1.70 USD/L for oil), painting, and greasing (at 2.5 USD/kg of grease). Replacement of components subject to wear and tear, such as stators, rotors, and gland packing, depended on the type of fluid being pumped. Thus, costs were based on actual data recorded by the maintenance personnel. Maintenance work on each piece of equipment was recorded and its cost was estimated along with the cost of replacing parts. The total cost for mechanical equipment operation was 4.4% of the total AOC.

Labour

Four levels of workers were involved in the operation of the plant, but not all were full-time: engineer (level A), administrative clerks (level B), technicians (level C), and labourers (level D). The times in person-hours for each level were estimated using the records of operation for 1 year. Times spent on each maintenance activity and to replace parts were calculated from actual cases and projected for a long-term operation. Table 9.8 shows the utilization of labour. The person-hours (PH) include time for pump calibrations (480 PH/year), collection of samples three times a week from 19 sampling points (468 PH/year), reading of recorders (150 PH/year), greasing and painting (240 PH/year), cleaning of equipment (45 PH/year), chipping away struvite formation in aerators (404 PH/year) and in pipes (56 PH/year), unplugging choked pipes, and routine maintenance, plant operation, and record keeping.

Table 9.8. Annual person-hours devoted to the operation of the PPP.

Unit operation	Level A	Level B	Level C	Level D	Cost (USD/year)
Raw wastewater pump station	292	554	264	548	7234
Primary sedimentation tank	292	635	222	550	7365
Anaerobic sludge digestion	292	462	222	542	6806
Oxidation ditch	52	219	222	539	5080
Secondary sedimentation tanks	292	459	222	539	6791
Aerated anaerobic lagoon	52	327	358	470	5689
Recycle water storage pond	52	219	222	254	4542
Sludge drying bed	52	219	222	944	5843
Total[b]	1376	3094	1954	4686	49350
Cost of labour (% of total)	12	28	18	42	4.4[c]

[a] Level A, engineers and senior research officers; level B, second division officers supervising the staff on the site; level C, technicians; level D, unskilled labourers.

[b] Grand total, 11 110 person-hours/year.

[c] USD/h.

Unit Operations

Based on the AOC of the Ponggol Pigwaste Plant (Table 9.7), the anaerobic digester had the highest operating costs. The AOC of the biogas digester was 24 656 USD/year (16% of total AOC), but the biogas it produced more than made up for these costs. When the floating aerators in the anaerobic lagoon were run on biogas, the total cost of electricity was reduced from 48 to 34%, a saving of 33 779 USD/year.

The total AOC per pig marketed from PPP was projected to range from 2.08 to 4.40 USD/year, depending on whether the minimum average SPP (16 500) or the total peak SPP (35 000) was used in the calculation.

Annualized Capital Costs

The Ponggol Pigwaste Plant was designed to operate for 15 years without major additions, except for the replacement of equipment, such as pumps, that had moving parts. The annualized cost was based on a 10% interest rate over a period of 15 years for the concrete structures and the mechanical equipment permanently installed in the plant. A 10-year return period was used on pumps (one on duty, one on standby). The straight-line depreciation method was applied to all the unit operations except for the anaerobic lagoon and the filter bed.

Table 9.9. Annualized costs of unit operations of the PPP.[a]

	ACC		TAC	
Unit operation	USD/ year	% ICC	USD/ year	USD/ PMY[b]
Raw wastewater pump station	18552	23	32062	1.00
Primary sedimentation tank	23252	22	34878	1.09
Anaerobic sludge digestion	194484	20	219139	6.85
Oxidation ditches	46616	19	80104	1.43
Secondary sedimentation tanks	23347	22	38320	0.68
Aerated anaerobic lagoon	65384	20	109195	1.95
Sludge drying beds	57480	19	64166	1.15
Recycle water pond	2295	19	7546	0.24
Total	431410	20	585409	14.39
USD/PMY[c]	7.70–13.48		10.45–18.29	

[a] ACC, annualized capital costs; TAC, total annualized costs; ICC, initial capital costs; PMY, pigs marketed per year.

[b] The cost per PMY in the last column is based on 20 000 SPP for the first three unit operations and 35 000 SPP for the rest. The average total annual cost can be assumed to be 14.39 USD per porker marketed, of which 10.87 USD was for financing the facilities and 3.49 USD/PMY for the operation of the plant. Financing costs were based on 15 years design life and 10% interest rate. Pumps were to be replaced every 5 years.

[c] For the annual operating costs (AOC), USD/PMY ranged from 2.75 to 5.83.

Based on the criteria listed above, the annualized capital costs amounted to 19–23% of the total initial cost, depending on whether the unit operation contained equipment with mechanical moving parts. Table 9.9 shows the annualized capital costs for eight unit operations and the entire plant.

Table 9.9 shows the total annualized costs, which are the sum of the annualized capital costs and the AOC (see Table 9.7). Of the eight major unit operations, the anaerobic digester has the highest annualized capital costs, but its annual operating costs are a small fraction of the capital costs, and less than the AOC for the aeration of the anaerobic lagoon.

Plant Performance

The plant was sampled at 19 points during the first year of operation. Samples were taken three times a week and, depending on the nature of the waste stream being sampled, they were analyzed for up to 10 parameters. Figure 9.6 illustrates the performance of the plant during the first year of operation. Table 9.10 shows the mean value for the 10 different parameters from each of the 19 sampling points.

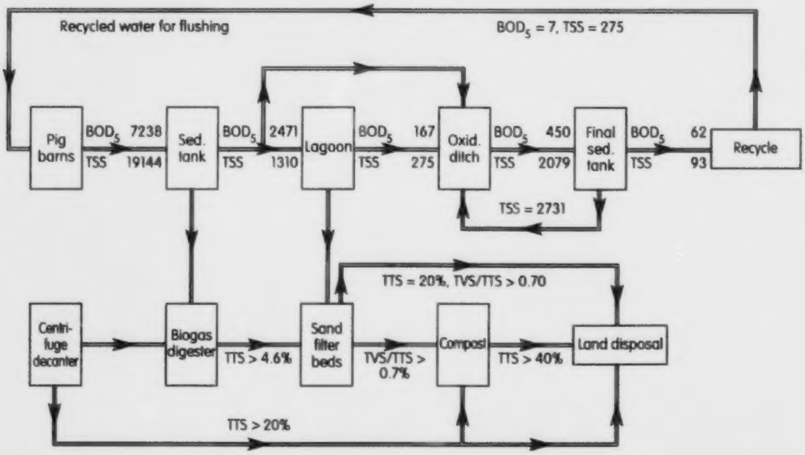
Recycled water for flushing
BOD5 = 7, TSS = 275
Pig barns
BOD5 7238
TSS 19144
Sed. tank
BOD5 2471
TSS 1310
Lagoon
BOD5 167
TSS 275
Oxid. ditch
BOD5 450
TSS 2079
Final sed. tank
BOD5 62
TSS 93
Recycle
TSS = 2731
TTS = 20%, TVS/TTS > 0.70
Centri-fuge decanter
Biogas digester
TTS > 4.6%
Sand filter beds
TVS/TTS > 0.7%
Compost
TTS > 40%
Land disposal
TTS > 20%

Fig. 9.6. Performance of the PPP in its first year of operation. The data are mean values (mg/L) from thrice weekly samplings of the PPP from May 1985 to April 1986.

Table 9.10. Mean concentrations of inflow and outflow in the major unit operations of the PPP.[a]

Sampling point	*n*	BOD_5 (mg/L)	COD (mg/L)	TTS (mg/L)	TVS (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg/L)	TAN (mg/L)	TNN (mg/L)	pH	Temp. (°C)
1. Raw wastewater	152	7238	24357	27401	21228	19144	15460	1533	522	—	6.50	29.0
2. Primary effluent	152	2471	4917	3768	2256	1310	1137	680	487	—	—	—
3. Primary sludge	181	—	—	25258	20561	19534	15947	1348	453	—	6.47	29.0
4. Digested sludge	184	—	—	51619	36630	45843	32957	—	—	—	6.84	30.4
5. Recirculated sludge	181	—	—	—	—	5222	3849	—	—	—	7.33	31.6
6. Digester effluent	181	1389	8254	9850	6150	8442	9119	1294	845	—	—	—
7. Biogas	(see Chapter 10)											
8. Mixed liquid[b]	108	450	2014	3522	2095	2079	1285	233	88	—	6.53	27.8
9. Coagulated effluent	81	24	311	1666	—	57	—	106	103	2	5.41	—
10. Clarifier effluent	108	62	461	1811	—	93	—	114	101	8	—	—
11. Alum sludge	(see Chapter 10)											
12. Clarifier sludge	108	—	—	4710	2866	2731	—	—	—	—	—	—
13. Decanter feed	(see Chapter 10)											
14. Decanter centrate	(see Chapter 10)											
15. Decanter cake	(see Chapter 10)											
16. Lagoon effluent	168	167	817	1865	743	275	212	493	416	2	7.66	—
17. Lagoon sludge	(see Chapter 10)											
18. Filter bed sludge	(see Chapter 10)											
19. Recycled water	181	7	64	670	—	375	—	13	16	19	6.68	29.0

[a] A sampling program was initiated immediately after the plant was commissioned in May 1985. Samples were taken 1–3 times a week at 19 strategic points. A minimum of 1 year of measurements is represented in this table. After the first year of sampling, individual sampling of some of the unit operations was carried out by graduate engineers and scientists who spent 2–4 months carrying out small research projects on the plant from 1976 to 1978. See Fig. 10.4 for location of sampling points. *n*, no. of observations; see list of Acronyms and Abbreviations for other definitions.

[b] Oxidation ditch.

Forum

Ideas, Issues, and Concepts for Assignments and Discussion

1. Trace the steps taken for the awarding of an engineering contract and the preliminary information necessary to prepare criteria for the selection of an engineering design consultant.
2. Prepare the specifications and major sections for an engineering design contract for a complicated plant to treat the wastes from a large feedlot in your area.
3. Identify the major items to be specified for the major equipment to be purchased in a full demonstration plant.
4. Prepare cost estimates for a major treatment plant based on local customs and current prices for engineering services and construction.
5. Identify and specify major unit facilities, unit operations, unit costs, and other related information for the proposed treatment plant.
6. Size facilities for solids stabilization (SST), most practical (MPT), and best demonstrated treatment technologies (BDT) for your location using the formulas and design parameters given in Tables 9.1, 9.2, and 9.3.

Chapter 10

Units of Treatment and Unit Operations

This chapter details the unit operations involved in the full treatment of pig wastes and wastewaters. The major units of operation are wastewater collection, solids separation, solids stabilization, liquid treatment, and resource recovery and recycling. The order and the combination of these units of operation determines the level of treatment and the characteristics of the effluent. The units may be grouped into treatment modules that can be implemented according to a schedule of compliance.

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Wastewater Collection

Collection of wastes and wastewaters depends on the type of pig pen flooring. In small farms with solid concrete floors, the wastes are washed into a channel for conveyance out of the production area. The traditional method of removing wastes in Singapore was to wash the pens twice a day with a high-pressure hose. In pens with slatted floors, the waste is collected in pits and either overflows or is released by opening sluice gates. The idea of a flushing channel under a slatted floor was introduced for two major reasons: odour moderation and conveyance of fresh excreta to the treatment plant. Fresh waste was essential for the energy and resource recovery components of pig waste treatment.

Solid Floors

From the standpoint of waste management, the critical elements in a solid-floor system are the quality of the concrete, the slope of the floor, and the design of the channel.

Concrete Quality

The concrete floor must be of high quality. If it deteriorated quickly, crevices and sharp edges would be produced that could harbour microorganisms that could affect the health of the pigs, reduce overall productivity, and cause discomfort to young pigs. A smooth surface would aid cleaning and movement, but would be too slippery for the pigs. The surface must provide good footing.

The recommended concrete for pig pen floors, driveways, alleys, and other structural concrete was a ratio of 0.55 water to cement with aggregates of 25–40 mm, a comprehensive strength of 20 N/mm^2, and a bulk density of 325 kg/m^3. The concrete surface of the pen floor should be swept at right angles to the direction of traffic, which, in a sloped pig pen, means parallel to the drain.

Floor Slope

For waste movement and cleaning, a slope of 1 in 5 (20%) was sufficient in solid floors draining toward a slatted area or an interceptor drain. Plans of pens and barns, with details on slope and other major features, are discussed in Chapter 4.

Drain

The slope of drains in a barn may be calculated using Manning's formula (see p. 303) with $n = 0.015$ for concrete, or the appropriate value for the material used and condition of the drain. Generally, the drain was a shallow rectangular channel if the pigs had access to it. However, outside the pens, the channels were standard drains with concave bottoms and sloped sides, which can convey the waste away at higher speeds and with less water than rectangular channels of the same dimensions. For scouring the drain, a flow velocity of 1.5–2 m/s is recommended. Generally, a slope of 1% would give this velocity. Unless sufficient slope is provided, waste solids settle in the drains and add to the malodour burden (see Chapter 6).

Slatted Floors

Slatted floors reduce the amount of water used in pen washing and moderate malodours. When combined with automatic flushing, slatted floors offer the best option for both odour abatement and waste collection and delivery. In tropical climates, solids hydrolyze when they are stored in pits or channels underneath slatted floors and can be removed without agitation. In cold climates, however, arrangements must be made for vigorous agitation before the slurry is pumped out. The requirements for a good system of slats is discussed briefly in Chapter 4.

Flushing

Automatic flushing siphons were first used in the early 1960s on a pig research farm at Iowa State University. They were first used in Singapore in 1978. By 1979, the longest flushing pig barns in the world were operating on the Industrial Farm Pte Ltd (IFPL). Several flushing systems were designed and operated because they were essential for the design of resource recovery processes, particularly the production of biogas.

The flushing system removes and transports wastes that have accumulated in the channel. A surge of water is created by the sudden release of water from a flushing tank at the head of the channel. The release of the water can be done manually or automatically with a siphon. For the water wave to remove the solids at the floor of the channel, scouring velocity must be at least 1 m/s. To attain such velocities, the gutter shape and slope must be carefully designed.

In a pig waste flushing system, the major parameters to be specified are the channel, the flow velocity, the volume of water, and the device that will activate the siphon action for automatic flushing. There is a minimum volume of water that must be released in a short time to create a transitory wave that scours the channel bottom and carries away the wastes from the channel floor. Some of the pertinent formulae and hydraulic principles involved are the momentum theorem, wave movement principles, dam break analysis approaches, and laminar flow factors. The depth of flow in the channel must be at least as high as the solids level in the channel. The more frequent the flushing of a channel, the lower the volume of water needed for each flush.

Flushing Siphon

The main components of a siphon and how it flushes are shown in Fig. 10.1. The advantage of a flushing siphon is that it has no moving parts and therefore requires minimal maintenance. All new farms in the Ponggol Phase III PFA installed flushing siphons.

The flushing action cannot be activated unless the discharge pipe trap is filled with water (A). As the holding tank is filled and the level of water rises above the level of water inside the bell (B), the air trapped in the bell pushes the water out of the trap (C). At the critical level, when the water level above the top of the bell begins to exceed the back-pressure from the water in the trap, the trapped air begins to escape and the water rushes out behind it (D). The escape of the trapped air can also be triggered with a vent pipe. As the water rushes out and the level falls below the side wall of the bell, a vacuum is created that sucks air into the bell to stop the flow (E). At this stage, additional air is sucked in through the vent hole to equalize the pressure (E). This restores the initial condition (A) and begins the cycle once again. Thus, by controlling the refilling rate of the holding tank, the frequency of automatic flushing can be controlled.

The design of a siphon involves calculating the size of the bell to fit the diameter of the pipe, the trap height, the volume of the tank, and the level of water above the bell. The design also involves locating the vent hole in the bell, which depends on the volume of air required in the bell to stop the flow of the siphon. The vent hole must be large enough to permit the required amount of air to be vented in no less than 15 s, but no more than 2 min. If the vent hole is too large, it allows too much air to enter and stops the siphon before the level in the tank reaches the bottom of the bell. The design requires many computations on a trial-and-error basis. A computer program was written to design siphons of different size and shape.

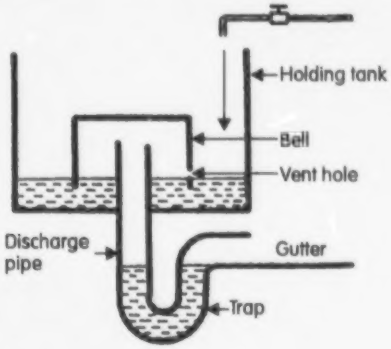
Water Volume

Based on laminar flow analyses and practical experience in Singapore, the volume of flushing water needed can be estimated by the following formula:

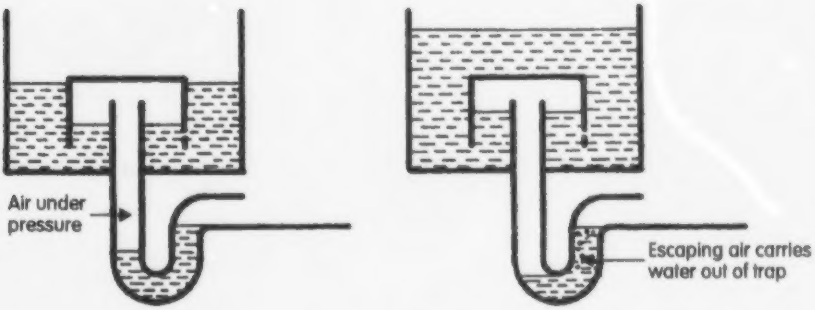
$$Q = Y_2 L W / 3$$

where Q is the flushing water volume (m^3), Y_2 is the depth of flow wave in front of the flushing water (m), L is the length of barn channel (m), and W is the channel width (m).

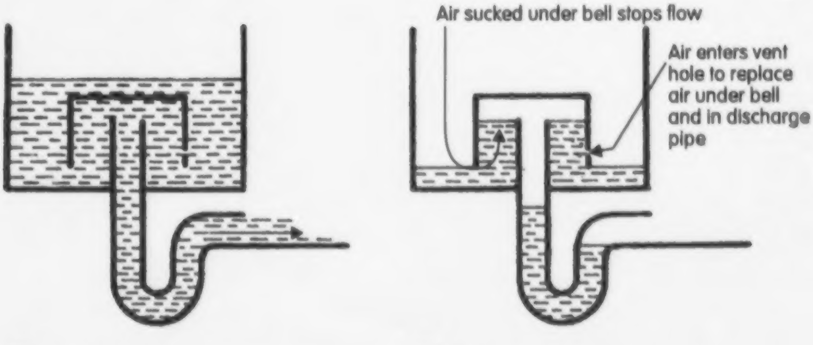
Trials carried out when flushing the 283 m long barn at IFPL showed that the waste solids scoured from the channel bottom mixed with the first 10–30% of the flushing water, which was advancing at the same rate as the frontal wave. In the 1 m wide channel under slatted floors, the


Holding tank
Bell
Vent hole
Discharge pipe
Gutter
Trap

Ⓐ Beginning to fill


Air under pressure
Escaping air carries water out of trap

Ⓑ Continuing to fill Ⓒ Ready to discharge


Air sucked under bell stops flow
Air enters vent hole to replace air under bell and in discharge pipe

Ⓓ Discharging Ⓔ End of discharge

Fig. 10.1. A flushing siphon.

minimum depth (Y) of flow had to be 0.075 m and the wave velocity (V), 0.9 m/s. In open-channel systems, the minimum values for Y and V were 0.05 m and 0.6 m/s, respectively. The lower minimum values in the open gutter flushing systems resulted from the pigs loitering in the gutter channel and loosening the waste. This helped distribute the solids more evenly across the channel.

The value of Q in the preceding formula was used to calculate the size of tank needed to hold the flushing water. At IFPL, the flushing tanks were constructed with a capacity of 20 m^3; after experimentation, however, it was found that a net capacity of 7 m^3 would be sufficient ($Q = (0.75)(283)(1.0)/3 = 7.1\ m^3$). To allow for some freeboard, the volume taken by the siphon-triggering device, and for severe conditions such as flushing after weeks of solids accumulation, the tank should be made 50–100% larger, that is, 10–14 m^3. The volume in the flushing tank can always be decreased by placing a piece of stone or block in the tank.

Channel

The dimensions of the channel were determined using Manning's formula:

$$Q = AV$$

$$= (2/3)[YW/(2Y+W)](S^{0.5})(1/n)$$

where A is the wetted area of the channel (m^2), V is the average velocity (m/s), Y is the average depth of flow (m), W is the bottom width of the channel (m), S is the hydraulic gradient, which may be assumed to be equal to the slope of the channel, and n is the roughness coefficient, which for smooth concrete surfaces is assumed to be 0.011.

The actual dimensions of the channel also depended on the following: the type of pigs contributing waste to the channel; the frequency of flushing, which varied from daily in farms that recycled water to occasionally in other farms, and also varied with the type of animal; and the need to provide some wastewater storage. Tables and graphs were prepared for each option and for the size of flushing device used.

Flushing Device

The bell over the discharge pipe generates the flushing action. Once the dimensions of the channel, tank, discharge pipe, and bell have been determined, the next step is to design the vent hole. The vent hole design is based on the principle of the compressibility of air, namely, the universal gas law $PV = RT$, which in this case resolves into the following equation:

$$P_1V_1 = P_2V_2$$

where P_1 is the barometric pressure, P_2 is the pressure when the trap is ready to release air, V_2 is the volume of air trapped in the pipes and in the bell just before the release of air, and V_1 is the volume required initially when the vent hole would be barely covered. The location of the vent hole (Fig. 10.1, E) is set to provide V_1 volume of air in the bell and thus produce the position shown in Fig. 10.1, A.

Siphon Construction

Because siphons have no moving parts and can be constructed of fiberglass, they last a long time without attention. It is critical, however, that they are constructed and installed properly. Failures after installation are usually due to poor construction. For example, if the siphon discharge pipe is not laid properly or the backfill is not adequately compacted, the pipes can crack or develop air or water leaks because of settling. Leaky pipe traps are difficult to diagnose and even harder to fix.

Some of the siphons failed because the farmers forgot to fill the pipe trap with water or tried to fill the tank too fast and not enough air entered through the vent hole. Plugging of the vent pipe or vent hole were two other common failures. The vent hole was easy to clean, but the vent pipe had to be back-washed with high-pressure water.

Manually Controlled Flushing

Several concepts for manually controlled flushing with mechanical valves, sluice gates, and tipping buckets were designed. However, none was as well accepted by the farmers as the flushing siphons.

Sump Sewer

For the flushing to work as designed, there has to be free flow over the edge at the end of the channel. This means there has to be a sump at the end of the channel whose liquid elevation during the flush is lower than the channel bottom. Otherwise, backwater conditions develop that slow the velocity of flow and allow solids to settle in the channel. To facilitate free flow, the receiving sump must have a capacity equal to the volume of the flush plus the volume of waste deposited in the channel between flushing plus freeboard.

At IFPL, the receiving sump was a 60-cm sewer that was designed to carry away the flow at the following rate (q):

$$\begin{aligned} q &= VY_2W \\ &= (0.9\ \text{m/s})(0.075\ \text{m})(1\ \text{m}) \\ &= 0.08\ \text{m}^3/\text{s} \end{aligned}$$

For open gutter flushing, Y_2 was 0.050 m. Therefore, a smaller carry rate was required.

Equalization Sump Tank

The design of the sump to collect the wastewater depends on the size of the stream being generated on the farm, the storage time required to homogenize the liquid before it is treated, and the rate at which the treatment plant is designed to receive the wastewaters. A major problem with automatic flushing devices such as siphons is that they can all flush at the same time and overload the sump.

In the case of the IFPL barns (see Chapter 9), where there were 20 flushing siphons, sizing the sump to take the flow of several tanks flushing at the same time would have been prohibitively expensive. After an exhaustive analysis of the probability of a number of siphons flushing simultaneously on any one day, it was decided to control the rate at which the treated water was pumped back to the siphons and have flow rate controls on the lines to each individual tank. Although the system could be automated, it was found to be safer and cheaper to have someone inspect the flow rates on each tank and adjust them so that no more than two flushed at the same time.

At the total waste recycling plant at PPRTI, the equalization tanks were large enough to store and agitate the entire wastewater stream for at least 1 day (see Chapter 1). In that case, the homogenization of the wastes was critical because of the nature of the experiments being conducted at that site. In the hot tropical climate of Singapore, 24-h storage of fresh waste modified the waste characteristics and reduced the amount of energy that could be recovered by anaerobic fermentation. Therefore, at PPP, wastes were pumped out immediately after they entered the sump.

Wastewater Properties

Table 10.1 shows the properties of the raw wastewater collected in the sump at PPP over a period of more than 1 year starting immediately after commissioning in May 1985. For other periods, the data are presented in conjunction with the unit process being analyzed.

Table 10.1. Characteristics of raw wastewater from PPP.[a]

					Value equaled or exceeded		
Parameter	Mean	SD (%)	Range	Count no.	20% of time	50% of time	80% of time
BOD_5 (mg/L)	7238	53	1500–19875	141	4100	6200	10000
COD (mg/L)	24357	64	2751–80981	141	12000	21000	38000
TKN (mg/L)	1533	48	340–3784	136	800	1400	2200
TAN (mg/L)	522	29	130–970	137	400	520	680
TTS (mg/L)	27401	76	2800–105000	142	1100	22000	43000
TVS (mg/L)	21457	78	1490–70400	142	7000	18000	32000
TSS (mg/L)	19144	85	533–84333	142	5000	15000	30000
VSS (mg/L)	14460	84	533–57600	142	4000	16000	25000
pH	6.00	7	5.00–8.00	142	6.15	6.55	6.85
Temp. (°C)	29	4	20–32	142	28.2	28.6	29.3

[a] Data were collected from the day of commissioning in May 1985 to the end of March 1986. Sampling was carried out three times a week. The standard deviation (SD), expressed as a percentage of the mean, along with range and frequency values indicate that there was great variability, particularly in the concentrations of solids. The data for the percentage of time a parameter is equaled or exceeded were derived from cumulative frequency curves.

[b] See list of Acronyms and Abbreviations for definitions.

Sump and Pump Well

One of the first and major problems encountered in PPP was the presence of large pebbles, plastic bottles, and syringes in the sump. These articles entered the pipeline and caused two major problems: plugging of pipes and damage to the rotor of the progressive cavity pumps that pumped the raw waste and settled sludge after primary sedimentation. The problem was ameliorated by placing a fine mesh screen in the sump intake. The screen was a vertical bar screen designed to hold back twigs, rags, and large particles.

The barns were supposed to be managed so that no materials other than pig excreta would be deposited in the flushing channel. Apparently, the workers who gave injections to the pigs as part of the routine health and vaccination programs threw the plastic containers into the slatted channel. Pebbles were carried into the channel by surface runoff during flooding. Although there was a conical bottom in the sump and the intake was 0.5 m above the bottom, pebbles were still sucked into the pump as they settled to the bottom. These are some of the reasons why under the modular treatment proposed for pig feedlot areas the raw waste went directly into a deep lagoon.

Solids Separation

Solids separation is one of the most common unit operations in a treatment plant. In simple systems, it can be combined with lagooning where the solids settle to the bottom, are stabilized, and are removed for dewatering. Dewatering is considered a different process.

The process used to separate the solids from the wastewater stream depends mainly on the size of the solids. Dissolved solids (TDS) are normally removed in a treatment plant by feeding them to bacteria (bioflocculation), algae, and fungi, which can then be harvested (as discussed in Chapters 7 and 8). Suspended solids (TSS) are normally removed by sedimentation, filtering, screening, or coagulation. Filtering with sand filter beds, filter belts, and filter presses was tried in Singapore. Coagulation in the final sedimentation tanks and during the centrifuging of treated liquids was also tried. In all cases, screens, filters, decanting centrifuges, and coagulants were most effective when used with stabilized solids rather than raw wastewaters. Therefore, they are discussed as dewatering processes rather than as solids separation.

The most effective method for separating solids from raw wastewaters was sedimentation, but even this process was not always reliable.

Screening

Four types of screens were purchased and tested in pilot plant operations: stationary "run-down" screens, rotating screens, vibrating screens, and bar screens. The bar screens were used where the wastewater stream contained surface runoff, including leaves and twigs. It was the standard textbook screen, and was fabricated for the wastewater inlets at both PPRTI and PPP.

The vibrating screen was a circular screen used to remove large particles and "hairballs." These balls tended to plug the digester pipes and did not digest; they are by far the most troublesome particles in the pig wastewater streams. They are formed from hair shed from the pigs and they do not disintegrate even when they pass through centrifugal pumps, which they can plug. Both the rotating and stationary screens tended to blind with raw wastewaters and are not recommended. The vibrating screens, although they also tended to blind, were satisfactory, but were too expensive to use in pig waste treatment. Their hydraulic capacity was low and they required energy to run.

Although they were considered seriously, screens, other than bar screens for large particles, were not used at PPP for two reasons: the unsatisfactory experiences mentioned previously and the question of what to do with screened out solids, which create malodours and other nuisances unless buried daily.

Sedimentation

The wastewater stream was split in two in the primary sedimentation tank: the liquid stream that constituted the liquid supernatant and the solids streams that constituted the primary sludge. Hydraulically, the liquid stream was 80% of the inflow. Table 10.2 gives the characteristics of the liquid supernatant from the primary sedimentation tank.

Table 10.2. Characteristics of the primary sedimentation tank supernatant.

Parameter	Mean	SD (%)	Range	Count no.	Value equaled or exceeded		
					20% of time	50% of time	80% of time
BOD_5 (mg/L)	2471	29	930–4980	139	1750	2400	3200
COD (mg/L)	49177	31	1911–10898	140	35000	47000	5800
TKN (mg/L)	680	52	50–4095	138	150	200	400
TAN (mg/L)	487	27	67–820	139	360	480	600
TTS (mg/L)	3768	43	1550–14700	142	2400	3500	4600
TVS (mg/L)	2256	55	850–10300	142	1500	2000	2700
TSS (mg/L)	1310	112	75–10333	142	400	1000	1800
VSS (mg/L)	1137	114	70–9000	142	300	800	1500

[a] See list of Acronyms and Abbreviations for definitions.

Separation of Metals

The separation of metals, most of which are bound to solids that are settleable, was accomplished in the primary sedimentation tank (Table 10.3).

Solids Stabilization

The two main methods of solids stabilization suitable for warm climates are anaerobic lagooning and anaerobic digestion. Anaerobic decomposition is the fermentation of organic solids in an oxygen-free environment.

Stabilization Standards

Although there was a plethora of standards for liquid treatment effluents, there were none for solids treatment. Therefore, criteria to measure solids stability and the standards to be met were developed (see Chapter 1, Table 1.2). The TVS/TTS ratio had to reach 0.7 for the solids to be considered stable. Moreover, the TTS was set at 20%.

Design Criteria

The design parameter chosen for anaerobic fermentation was organic loading rate (OLR) expressed in terms of TVS. When OLR was less than 0.2 kg TVS/m^3 per day, the stabilization process was considered to be lagooning. For an OLR of more than 0.2 but less than 0.5 kg TVS/m^3 per day, the process was called uncontrolled digestion. If the OLR was greater than 2.0 kg TVS/m^3 per day the process was called high-rate digestion and was controlled with continuous or intermittent mixing in enclosed tanks.

After the OLR and the concentration of volatile solids are determined, the hydraulic detention time (HDT) is calculated. For lagoons, HDT is in the range of months to years. In high-rate digestion, HDT is in the range of days to months.

The rate of decomposition is exponentially proportional to temperature. Based on water temperatures in lakes during the coldest month of the year, the design OLR for lagoons was established at 0.14 kg TVS/m^3 per day. The highest daily OLR of 0.20 kg TVS/m^3 was based on a monthly average water temperature of 25°C during the coldest month of the year.

The sizing of the fermentation vessel is calculated by making relevant assumptions about what happens in the solids stabilization process. It is assumed that the following steps occur during solids degradation and lagooning.

1. All the dissolved solids (TDS) escape in the effluent. Actually, some of the dissolved organics are used by bacteria, which may flocculate and settle, and some are gasified. However, for practical purposes, it is

Table 10.3. Separation of metals (mg/L) in the primary sedimentation tank.

Metal	Raw wastewater		Supernatant		Reduction[a] (%)	Primary sludge	
	Mean	Range	Mean	Range		Mean	Range
Chromium	13	1–34	3	1–5	77	12	1–32
Copper	6	2–13	1	1–2	88	7	4–11
Iron	46	26–66	6	5–8	92	50	42–57
Magnesium	181	110–230	84	75–99	74	156	133–175
Phosphorus	560	328–695	185	132–350	83	563	455–925
Potassium	469	400–645	350	311–457	61	427	388–520
Sodium	183	174–205	117	103–128	67	172	143–192
Zinc	13	7–20	2	2–3	91	13	12–15
Arsenic	0.03	0.03–0.04	0.02	0.01–0.05	—	0.03	0.02–0.05
Cadmium	0.04	0–0.05	0.03	0–0.05	—	0.03	0–0.005
Lead	0.36	0.15–0.60	0.09	0–0.25	90	0.36	0.10–0.60
Mercury	0	0–0.005	0	0	—	0	0–0.04

[a] Reduction percentages are based on mass rates, i.e., they include the difference in volume of flow.

assumed that the organics produced from the decomposition of suspended organics replenish the dissolved organics in the original influent.

2. 80% of TSS settles to the bottom of the lagoon, which, for an animal population unit (APU = 100 kg animal live weight; see Chapter 5), would amount to 0.56 kg/APU per day (0.80 × 0.69 kg TSS/APU per day, from Table 5.1).
3. 80% of the settled solids are volatile, which means 0.45 kg VSS/APU per day settles to the bottom.
4. During the 365 days that the solids are retained (solids retention time, SRT = 365 days) at the bottom of the lagoon, 60% of the volatile solids degrade into gases or dissolved solids and leave the bottom of the lagoon. The amount remaining is 0.18 kg VSS/APU per day.
5. The inorganic portion of the settled suspended solids does not undergo any degradation that would change its weight. Thus the ash content remains the same: 20% of the TSS or 0.14 kg SFS/APU per day (SFS, suspended fixed solids).
6. The total solids remaining are the sum of 4 and 5: 0.32 kg TSS/APU per day. This is the amount of stabilized solids that must be stored for the SRT specified: 1 year. In fact, a year was more than enough in the warm climate of Singapore; 60–100 days was sufficient because of the high water temperature of 27–29°C. However, to ensure that desludging is not needed for at least the first year, an SRT of 1 year is safe.
7. The retained solids are stored under the hydraulic pressure of the deep lagoon. In one lagoon, which had been in operation for more than a year before being desludged, the TTS in the sludge was 13% at the bottom and 3% at the top. The average was assumed to be 5% TSS (0.05 kg TSS/L of liquid). The volume occupied by the stabilized solids was calculated to be 6.40 L/APU per day. That is a safe design value based on the data presented in Table 10.4, which indicate that the sludge pumped from the bottom of the PPP lagoon in 1987 averaged above 5% TTS and 5% TSS.
8. If the lagoon is to be desludged at the end of the design SRT (1 year), then the volume required per pig is 2 336 L/APU or 1.26 L/SPP, where the average animal live weight is 54 kg (see Chapter 5).

Table 10.4. Characteristics of lagoon bottom sludge.

Date, 1987	TSS (%)	TTS (%)	TVS (%)	TVS/TTS	Copper (mg/L)	Zinc (mg/L)	Lead (mg/L)
17 Mar.	5.03	5.35	2.96	0.55	169	220	0.18
18 Mar.	5.57	6.05	3.35	0.55	148	205	1.5
23 Mar.	5.43	5.60	3.10	0.55	176	243	0.1
11 May	5.57	6.28	3.36	0.54	—	—	—
22 May	5.63	6.53	3.58	0.55	—	—	—

Based on this analysis and the design SRT, the OLR for solids stabilization was calculated to be 0.53 kg TVS/m^3 per day, and the stabilized solids to be removed from the lagoon bottom, 0.32 kg TTS/APU per day.

Anaerobic Lagoon

One of the earliest and simplest methods to treat wastes is to dig a large hole to contain the wastes and allow them to break down. Anaerobic lagoons are deep (2 m or more) and are loaded at such high organic rates that any free oxygen is quickly depleted. The lagoon remains anaerobic throughout its depth except for an extremely shallow surface layer. In the absence of oxygen, anaerobic bacteria break down the wastes to form carbon dioxide, methane, and other gases.

The main advantages of anaerobic lagoons are low land requirements, low construction cost, and no energy needs. However, odour is a major disadvantage. In Singapore this was overcome by modifying the concept of the anaerobic lagoon to include surface aeration. However, in this section, only the effectiveness of the anaerobic lagoon as a solids stabilizing process is discussed.

Solids Loading Rates

Table 10.5 shows the solids loading rates of the modified anaerobic lagoon at PPP from 8 to 15 April 1987. The lagoon served two purposes: liquid treatment and solids stabilization.

Sludge Accumulation

Sludge accumulated to a depth of more than 3 m in the lagoon near the inlet point, but was less than 0.5 m deep 50 m away from the inlet. The bottom sludges averaged more than 7% TTS, whereas the TTS concentration 1.5 m below the surface was less than 1%.

Sludge Stability

Below the aerators, where there was adequate mixing, the TVS/TTS ratio was about 0.3. At a depth of 3 m, the TVS/TTS ratio was about 0.55.

Table 10.5. Solids loading in the aerated anaerobic lagoon.

		TTS		TVS		TSS	
Date, 1987	Liquid in lagoon (m^3)	Inflow (kg/day)	Daily loading (kg/m^3)	Inflow (kg/day)	Daily loading (kg/m^3)	Inflow (kg/day)	Daily loading (kg/m^3)
8 Apr.	23571	2437	0.10	1537	0.07	1537	0.07
9 Apr.	23571	2338	0.10	1458	0.06	1529	0.06
10 Apr.	23571	2980	0.13	2162	0.09	2180	0.09
13 Apr.	23348	3369	0.14	2452	0.11	2775	0.12
14 Apr.	22977	3434	0.15	2505	0.11	2124	0.10
15 Apr.	22683	4118	0.18	2860	0.13	2919	0.13
Mean	23287	3113	0.13	2162	0.10	2177	0.10

At the bottom of the lagoon, where there was less biological activity because of the quiescent condition and higher pressures, the ratio was as high as 0.62, but always less than the design value of 0.70.

Lagoon Desludging

Because of the unevenness with which sludge accumulates, the desludging frequency may be less than the SRT assumed in the design. However, the major factors affecting the frequency and rate of desludging are the hydraulic capacity of the sludge drying bed or mechanical dewatering device and the drying rate and thus the time it would take the sludge to dry to the required solids content of 20%.

Anaerobic Digestion

Anaerobic digestion is widely used to stabilize concentrated organic wastes. It differs from lagooning in that the OLR is much higher and, therefore, it requires less HDT: as much as ten times less volume per unit of waste than lagooning. In digestion, the waste is fermented in sealed digesters and oxygen is excluded. Under these conditions, anaerobic bacteria thrive and convert up to 90% of the degradable organics into methane and carbon dioxide (CH_4/CO_2 content is usually 65/35). Temperatures above the mesophilic range (35°C) are required to achieve high process efficiencies and resource recovery.

The process for stabilizing solids in the digester is the same as in the lagoon, except that mineralization is accomplished within an HDT of only 10–15 days. The solids retention time in a digester was the same as the HDT because the entire contents of the digester were agitated daily, and before withdrawal of the sludge solids. However, mineralization was not as complete in the digester. The TVS/TTS ratio of the digester sludge was 0.71; it was 0.55 for the lagoon sludge.

Table 10.6 gives statistics on the influent and effluent sludge of the anaerobic digester at PPP. The data indicate that the TVS/TTS ratio was higher than 0.70 more than 50% of the time. The variability of the incoming primary sludge was much greater than that of the digested sludge, which was comparatively uniform. The digested sludge averaged over 5% TTS, but the incoming primary sludge averaged only 2.5%, which was less than the design value for the sedimentation process.

Dewatering of Stabilized Sludge

Dewatering of sludges from cesspits, lagoons, and digesters was carried out in timber and sand filter beds, in filter belt presses, and with decanting centrifuges. The tests were conducted in full-scale plants at PPRTI, at the Ng farm in the Phase II PFA, at several farms in Phase I PFA, and at PPP in Phase III PFA. An economic feasibility analysis showed that sand filter beds, decanting centrifuges, and filter belt presses cost about the same per pig marketed, assuming that the machines were operated 18 h/day.

Table 10.6. Comparison of inflow and outflow sludge in the PPP digester.

	TTS (mg/L)	TVS (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Temp. (°C)	TVS/TTS
Digested sludge (S_4)							
Mean	52414	37111	46101	33142	6.88	30.4	0.71
SD[a]	41%	39%	43%	43%	4%	5%	8%
Count	178	178	178	178	178	146	180
Min.	8600	5600	2950	2150	5.73	27.0	0.50
Value equaled or exceeded							
20% of time	35000	27000	32000	23000	6.75	29.0	0.68
50% of time	50000	35000	43000	32000	6.90	29.4	0.73
80% of time	70000	50000	61000	46000	7.15	30.0	0.76
Max.	133200	81800	122333	76667	7.67	38.0	0.83
Primary (influent) sludge (S_3)							
Mean	25407	20682	19650	16041	6.51	29.2	0.75
SD	97%	103%	109%	112%	8%	3%	0.12
Count	169	169	169	169	168	136	169
Min.	1760	1650	800	400	5.23	27.0	0.43
Value equaled or exceeded							
20% of time	6000	5000	4000	3000	6.15	27.8	0.68
50% of time	15000	12000	11000	8000	6.55	28.8	0.77
80% of time	50000	40000	40000	30000	6.85	29.6	0.83
Max.	100100	92500	84667	72000	7.82	31.0	0.96
Reductions (%) in digester $(S_4-S_3)/S_4$							
Mean	52	44	57	52	5	4	−5
Min.	80	71	73	81	9	0	14
Value equaled or exceeded							
20% of time	83	81	88	87	9	4	0
50% of time	70	66	74	75	5	2	−5
80% of time	29	20	34	35	4	1	−9
Max.	25	−13	31	6	−2	18	−15

Note: See Fig. 10.4 for location of sampling points S_3 and S_4.

[a] SD, standard deviation.

Two types of filter beds were tried initially on the farms: a timber bed and dirt–sand filter beds. Experiments showed that a batch could be dried in 1 day and would produce material that had a moisture content of 69% (31% TTS). The average solids recovery from the beds ranged from 13.4 to 37.0 kg/m^2 (Table 10.7). The average daily solids production was 0.23 kg/SPP.

Timber Drying Bed

To reduce the manual labour required to handle the dried sludge, a timber bed was constructed and operated for several months to handle the

Table 10.7. Solids production from timber and dirt–sand drying beds.

Bed	Period (weeks)	Batches (no.)	Bed area (m^2)	TTS		
				kg	kg/batch	kg/m^2
Timber	3	12	4.4	705	58.8	13.4
Timber	4	15	4.4	2440	162.7	37.0
Timber	8	20	4.4	1987	99.4	22.6
Dirt–sand	6	7	11.75	2144	306.3	26.1

solids from a 500-SPP farm. The solids were removed with a skid-row tractor equipped with a front-end loader. The solids were also piled up and allowed to compost. Both of these ideas were developed into unit operations for PPP.

Sand Filter Beds

The design of the battery of six filter beds at PPP was a culmination of 6 years of experiments with sand filter beds, which ranged in size from 2 to 100 m^2 at several sites. The unique feature that developed from these tests was the successful use of steel tracks for the mechanical harvesting of dried sludge.

Only five of the six open sand filter beds, each having a surface area of about 600 m^2, were used to dewater sludge from the aerated anaerobic lagoon (AAL) and the 1 500-m^3 anaerobic digester. The beds, which were 40 cm thick, were constructed with a 10 cm thick crushed stone base, a 15-cm intermediate crushed stone layer, and a 15-cm sand layer. Underdrainage (leachate) from the beds was conveyed to the AAL by 100 mm diameter UPVC perforated pipes. Each bed was surrounded by a 50 cm high concrete wall to retain up to 45 cm of sludge slurry.

A system of pipes and a mobile pumping station were used to withdraw the stabilized sludge from the bottom of the lagoon and to pump it into the drying beds for dewatering (see Chapter 9). The digested sludge was conveyed by gravity from the digester tank to the sand filter beds.

The Drying Process

There were two distinct phases once the sludge was loaded into the drying beds. At first, the free water in the sludge drained as leachate and was returned to the lagoon. Because the rate of evaporation was slower than the drainage rate, loss of water by evaporation during the drainage phase was negligible. After the drainage phase, the bonded water started to evaporate and the sludge started to dry and crack. Crack width was used as a measure of sludge drying: as the sludge dried, crack width increased.

Humidity, temperature, air velocity, rainfall, and intensity of solar radiation affected the drying process. These factors were monitored and used to calculate the theoretical rate of drying and heat transfer equations.

Table 10.8. Characteristics of influent sludge and drained leachate from sand filter beds.

Sample	TTS (mg/L)	TSS (mg/L)	TVS (mg/L)	TVS/TTS	COD (mg/L)	BOD_5 (mg/L)	pH	Copper (mg/L)	Zinc (mg/L)	Lead (mg/L)
Digester sludge, depth 15 cm										
Influent sludge	10800	9000	7100	0.66	10859	500	7.29	11.3	22	0.15
Leachate, 1st day	2650	850	1250	0.47	1476	120	7.62	2.4	1.9	0.10
Leachate, 2nd day	2100	133	900	0.43	750	50	7.62	0.5	0.3	0.04
Lagoon sludge, depth 15 cm										
Influent sludge	53500	50333	29600	0.55	—	—	—	169	220	0.18
Leachate, 1st day	3550	133	2000	0.56	750	50	6.55	1.6	0.7	0.04
Leachate, 2nd day	3450	63	1850	0.54	786	—	6.70	0.7	0.4	0.04
Lagoon sludge, depth 30 cm										
Influent sludge	56000	54333	31000	0.55	—	—	—	176	243	0.10
Leachate, 1st day	2450	47	1050	0.43	501	—	6.36	0.5	0.8	0.05
Leachate, 2nd day	2950	64	1250	0.42	—	—	6.95	0.8	0.4	0.05
Leachate, 3rd day	2900	35	1000	0.34	—	—	7.08	0.5	0.3	0.04
Lagoon sludge, depth 40 cm										
Influent sludge	60500	55666	33500	0.55	—	—	—	148	205	1.50
Leachate, 1st day	5300	133	3100	0.58	589	—	6.39	1.0	0.8	0.04
Leachate, 2nd day	3200	275	1500	0.47	875	—	7.24	1.1	0.5	0.05
Leachate, 3rd day	2800	50	1050	0.38	—	—	7.33	0.7	0.3	0.04

Sludge Characteristics

The characteristics of the sludge pumped into the drying beds and of the leachate are given in Table 10.8.

Leachate Percolation

The flow of percolated leachate from the sand filter beds started immediately after loading and continued for 1–3 days (Fig. 10.2). If there was no rainfall, drainage was negligible after 2 days. If it rained during

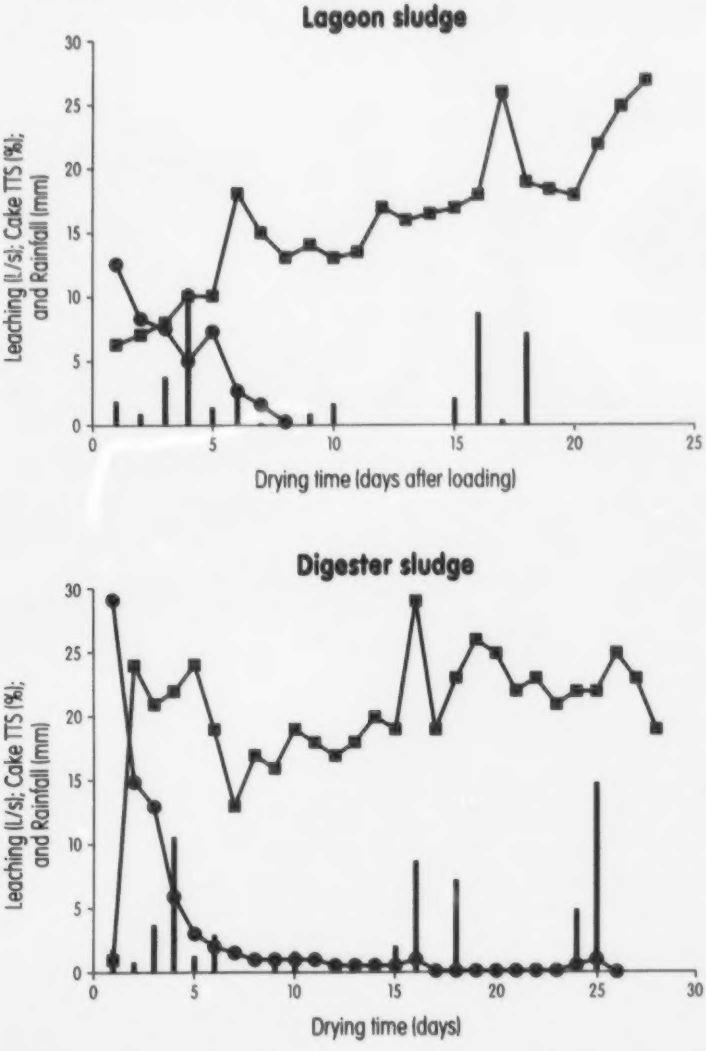


Fig. 10.2. Patterns of change in TTS (■) and leaching rates (●) of sand filter beds for lagoon sludge and digester sludge; bars show daily rainfall.

the initial drainage phase, it took longer for the percolation to cease. High rainfall during the 3 days that it took to load the filter beds caused the change in leachate flow pattern shown in Fig. 10.2. After the rain stopped, the flow pattern returned to its previous trend. If the sludge cracked before the rain, the rainwater passed easily through the system. Therefore, open sludge drying beds perform well in the tropics in spite of the rains. After cracks develop, rain does not cause a problem.

Leachate Water Quality

The quality of the liquid drained from the sludge depended on the initial solids content and characteristics of the sludge. For the same depth of sludge (15 cm), the volume of liquid drained from digester sludge was about five times greater than from lagoon sludge (23 m^3 vs 5 m^3). This was as expected because the water content of the digester sludge was five times higher. The volume of leachate (free water content of the sludge) was 26% of the original volume of the digester sludge and only 5–8% of the lagoon sludge. This indicates the higher water-shedding capability of the digester sludge. Table 10.8 shows the characteristics of the sludge and the leachate at various depths of operation.

Sludge Cracking

After the drainage phase, dewatering was caused mainly by evaporation. The sludge began to crack with minute hairline cracks, and then with secondary and tertiary cracks throughout the surface of the drying bed. Bubbles first appeared on the surface along the steel tracks and later throughout the filter bed surface.

Sludge cracks appeared after the drainage phase (2–3 days) and increased steadily. As the crack width increased, TTS increased and the sludge started to dry. Therefore, crack width was used as an indicator of sludge drying. Crack width for the 30 cm thick sludge developed most rapidly and increased to a maximum of 58.5 mm in 7 days. Once the maximum width was reached, no amount of rain decreased the crack width. The rainwater simply passed rapidly through the cracks as leachate through the drying bed.

Digester sludge at the same depth as the lagoon sludge (15 cm) crusted and cracked faster. The rate of crusting was defined as the difference between maximum and initial crack widths divided by the number of days elapsed between these two states (mm/day). The crusting rate of the digester sludge was 6.13 mm/day; lagoon sludge averaged 2.93 mm/day. The crusting rate for 3-cm lagoon sludge was 4.07 mm/day; for 4-cm lagoon sludge, the rate was 4.16 mm/day. In these experiments, drainage was completed in 2 or 3 days, and the solids content was 27.5% for digester sludge and 10–11.5% for lagoon sludge.

The 15-cm sludge shrunk to an average thickness of 9.2 cm after 17 days (5.4 mm/day), which reduced the sludge volume by about 39%. The drying rate of digester sludge was 6.03 mm/day; lagoon sludge averaged 2.03 mm/day for the same depth. This difference was caused by different sludge characteristics, such as initial solids content and moisture content.

For lagoon sludge, the drying rates were 2.03, 3.07, and 2.93 mm/day for sludge depths of 15, 30, and 40 cm, respectively. There seemed to be no relation between drying rate and sludge depth.

Loading Method

Two beds were filled with 15 cm (87 m^3) of lagoon sludge (approximately 5.60% TTS) and allowed to dry naturally until the TTS reached 20%. Another bed was loaded continuously with digester sludge (approximately 1.08% TTS) at 87 m^3/day for a period of 5 days, to get the same loading as the beds with lagoon sludge, and allowed to dry until the TTS reached 20%. The solids loading rates were 8.6–9.8 kg TTS/m^2. The lagoon sludge was black, homogeneous, and creamy like heavy clay dissolved in water. The sludge from the digester was light black, nonhomogeneous, and contained coarse particles, pig hairs, and worms.

When the drying beds were loaded, the lagoon sludge distributed itself uniformly over the bed, whereas most of the coarse particles in the digester sludge accumulated near the inlet splash pad and the lighter particles were carried away from the inlet pipe to the opposite side of the bed. Therefore, sludge thickness was higher at the inlet side and decreased slightly toward the ramp side.

Leachate from the lagoon sludge was clear and had a flow rate of approximately 0.12 L/s, which was less than the flow rate of the digester sludge leachate (0.30 L/s). However, leachate from the digester sludge was more turbid and had more colour. The drainage period for lagoon sludge was about 5 days. Rain on the 14th day of drying percolated through the sand filter bed almost unchanged. The digester sludge was loaded continuously for 5 days and the drainage period lasted 7 days (Fig. 10.2).

The TTS content of lagoon sludge cake increased with time, with slight fluctuations as a result of changing weather conditions (Fig. 10.2). Lagoon sludge cake reached 20% TTS in 12–16 days. The TTS content of digester sludge cake increased sharply on the 2nd day after loading. Additional digester sludge loading the next day resulted in a lower TTS content of the sludge. Decrease in digester sludge TTS was due mostly to rainfall and high humidity. It took 12–17 days to dry digester sludge to 20% TTS. However, there was some water on the surface of the bed near the ramp.

A drying front boundary between the wet and the dry surfaces of the sludge did not occur in the lagoon sludge because it dried uniformly throughout the bed. A drying front originated around the splash pad with digested sludge and moved toward the ramp. The lagoon sludge acted like an absorber plate in a solar collector because of its black colour. The temperature difference between the top and bottom layers in the lagoon sludge stimulated evaporation. A temperature difference did not exist in the digester sludge, probably because of its porosity. Cracks developed on the surface of the digester sludge 1 day after loading. This may be caused by a lack of bonding material between the sludge particles as the water drained. Cracks developed slowly and reached a width of 30 mm at a TTS content of 20%. Cracks in the digester sludge bed were greatly affected by rainfall because the the coarse particles tended to absorb moisture easily and expand. The dried sludge was thicker near the splash pad and was brown in colour.

Sludge Harvesting

The sludge was harvested from the drying beds with a skid-steer tractor that had a front-end loader. This type of tractor had several advantages.

- It was easy to operate because of its manually controlled hydraulic drive system, steering system, and four-wheel drive.
- It was easy to maneuver.
- The drive wheels were always parallel, which helped the skidder to travel straight on the tracks.
- The front-end loader could be used to scrape and haul the sludge to the compost site.

The loader had a bucket capacity of 0.30 m^3, the bucket was 159 cm wide, the turning radius to bucket edge was 190 cm, and the maximum speed was 10–13 km/h. During harvest, the forward and reverse speed along the tracks was about 7 km/h. Two systems to harvest and place the lagoon and digester sludge were studied: placing the sludge in windrow piles and loading the sludge directly into a dump truck. The digester sludge, which at the time of harvest had 43% TTS (57% moisture content), was harvested at a rate of 18 m^3/h and used 2.13 L of diesel fuel per hour. The harvesting rate when the sludge was loaded on a truck was 13 m^3/h.

Effect of Solids Flux Rate

Sand filter beds were studied at many sites. The solids loading rates from one such study at PPRTI in 1987 are presented in Table 10.9. Solids flux rate (SFR) was based on the number of drying days to obtain a total solids content of 20%, the depth of sludge, and the initial solids content. The SFRs for the sludge taken from the 15-m^3 high-rate digester were 720, 500, and 420 g/m^2 per day for the 15, 25, and 35 cm depths, respectively. It took only 4 days to reach 20% TTS. Based on this and other studies, it was concluded that the sludge could be dried in 14–16 days to an SFR of about 800 g/m^2 per day in both small and large sand filter beds.

Table 10.9. Solids flux rate (SFR) tests with sand filter beds.

Drying bed size	Sludge depth (mm)	Initial TTS (%)	Time to reach 20% TTS (days)	SFR (g/m^2 per day)
2.0 m × 2.08 m	150	1.92	4	720
2.0 m × 2.08 m	250	0.82	3	500
2.0 m × 2.08 m	350	0.60	3	420

Sludge Composting

Composting is the aerobic, thermophilic decomposition of organic wastes. The decomposition is done by aerobic organisms, primary bacteria, actinomycetes, fungi, and protozoa. The main factors in composting are moisture content, aeration, carbon to nitrogen (C:N) ratio, phosphorus content (TPP), potassium content (TKK), temperature, pH, particle size, and micronutrients and microenvironmental conditions conducive to the growth of aerobic organisms.

The optimum initial C:N ratio ranges from 30 to 50. During composting, the microbial succession develops rapidly. The process starts promptly and the optimal temperature for organic matter degradation (55°C) is attained within a few days. The thermophilic temperatures act as strong and comparatively fast bactericides. Decomposition of organic matter depends on the presence of moisture, and the optimum moisture content is 40–60%. The intermediate products of aerobic decomposition are carbon dioxide, water, and heat.

There are various methods of composting. One of the simplest and most widely used is windrow composting. The composting materials are shaped into heaps, which shed rainwater and preserve temperature and humidity. Periodically, the heaps are turned manually or mechanically. Typical composting time is 20–40 days.

Windrow Composting

Dried sludge from the open sand filter beds was composted in open windrow piles (3 × 2 × 1 m high) with and without mixing for periods of 30–40 days. Nothing was added to the sludge during composting, and mixing, when done, was once every 5 days. The C:N ratio and moisture content were not adjusted.

In the digester sludge, the temperature in the middle of the pile immediately reached 60°C; in the lagoon sludge, however, the thermophilic temperature was reached after 5 days. For composting, the optimum C:N ratio should range from 30 to 50 and the moisture content should be 45–50%. Although these criteria were not fulfilled in these experiments, thermophilic composting did occur. The moisture content of the piles ranged from 34 to 41% and the initial C:N ratio was below 20 for the digester sludge and less than 11 for lagoon sludge (Table 10.10).

No significant changes in TKN, TAN, TPP, or TKK were noted during composting. In the lagoon sludge, the temperature of the mixed piles increased faster than that of the unmixed piles. The temperature reached the thermophilic range after 1 week and stayed within this range for about 20 days. Mixing accelerated the growth of microorganisms and resulted in an increase in temperature. Furthermore, aeration, which is necessary for composting, is improved with mixing. Mechanical mixing can also reduce particle size and optimize microbiological action because of the increase in surface area.

During the last stage of composting, temperature decreased because the

Table 10.10. Composting of digester sludge and lagoon sludge.

	Unmixed pile				Mixed pile			
	Digester sludge[a]		Lagoon sludge[b]		Digester sludge[a]		Lagoon sludge[b]	
Parameter	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Temp. (°C)	58.7	54.9	31.8	37.7	58.7	59.8	31.5	46.0
Moisture content (%)	54.3	40.3	36.8	32.3[c]	45.8	41.3	41.0	34.3[c]
TVS (%)	28.2	32.6	23.5	26.6	32.7	27.8	27.2	26.1
Carbon (%)	14.2[d]	14.4	10.2	10.4	16.2[d]	13.2	10.6	10.1
TKN (%)	0.94	1.72	1.60	1.66	1.07	1.40	1.99	1.75
TAN (%)	0.19	0.38	0.35	0.35	0.28	0.46	0.32	0.47
C:N ratio	11.40	8.40	6.34	6.28	16.60	9.90	5.32	5.78
TPP (%)	1.87	2.21	2.97	2.99	1.87	2.24	2.73	2.93
TKK (%)	0.13	0.13	0.14	0.14	0.28	0.13	0.14	0.14

Note: See list of Acronyms and Abbreviations for definitions.

[a] Time = 32 days for temperature and 26 days for other parameters.

[b] Time = 28 days for temperature and 25 days for other parameters.

[c] 21st day.

[d] 3rd day.

microorganisms were not active, either because of a shortage of food or other inhibiting factors. Temperature was higher at the top and lower at the bottom of the piles. Accordingly, the depth of the piles may affect heat preservation: if the pile is low, more heat will be lost.

The C:N ratio was 5.0–6.7 for the unmixed piles and 5.1–7.0 for the mixed piles of lagoon sludge. The low initial C:N ratio suggests the need to mix to distribute the nutrients. In mixed piles, the carbon content was almost constant after 21 days and the temperature began to fall after 23 days, which suggests that composting was complete.

Effect of Inoculum

The temperature in a new pile inoculated with 10% composting sludge did not increase to the thermophilic range more quickly than sludge that had not been inoculated. However, 3-week-old dried sludge could not be composted even if it was inoculated.

Dominating Fungi

Four dominant genera of fungi were isolated from 50 compost samples. One was identified as *Aspergillus* sp. and two were *Humicola* spp. One isolate could not be identified.

Aspergillus sp. PS4 was thermotolerant. It could grow at 15, 20, 30, and 47°C, with optimum growth at 30°C. The other genera were thermophilic, with an optimum temperature of 47°C. They could grow at 15–20°C. *Humicola* spp. PS1, PS2, and PS3 and *Aspergillus* sp. PS4 were the dominant species during the most active period of composting (45–50°C). When the temperature reached 45°C, fast growth of these fungi was observed. This temperature was the lower limit for the thermophiles.

During this period, white to grayish white and blue-green mycelia completely covered the inside of the pile (20–40 cm from the top).

The final compost product averaged 2% TKN, 2% TPP, and 0.14% TKK. The final compost was odourless and free of flies and other insects. Open sand filter beds and windrow composting were, therefore, good ways to manage pig waste sludge and conserve nutrients for recycling.

Pigs-on-Litter Composting

One idea promoted by a Japanese manufacturer of enzyme additives was to rear pigs on sawdust litter, which would absorb the urine and stabilize the solids. The concept had been tried in the cold climate of Japan and in the semitropical climates of Taiwan and Hong Kong, but it had not been tested in a hot, humid climate such as that of Singapore.

In the deep-litter system, a 20-cm mixture of fine and coarse sawdust is placed on a level concrete pen floor. A uniform size sawdust is not recommended because it inhibits the movement of air and water through the litter. Also, the sawdust should not be rough because the sharp particles could irritate the skin of small pigs. The litter had to be turned over several times a week to distribute the wastes thoroughly and promote biodegradation. There were also products marketed as beneficial additives. Fresh sawdust or water had to be added regularly to maintain the proper moisture content in the litter. Drinking nipples were located outside the pen wall to keep spilled and leaked water away from the litter.

Decomposition of the urine and organic solids within the sawdust mixture was carried out under aerobic conditions. This caused the floor temperature to rise, which is desirable in cold climates, but not in the tropics.

With the cooperation of the Japanese manufacturer, experiments were set up in Singapore in 1986 and in Malaysia in 1987. The Singapore trial was unsuccessful because the necessary moisture controls were not used. The sawdust became wet, which allowed flies to breed and malodours to be released. The trial at the pig research farm of the Malaysian Agricultural Research and Development Institute (MARDI) used 48 growing–finishing pigs to compare the conventional solid floor and daily hosing with the deep-litter system. The moisture content of the litter mixture was maintained at 50–65%, the C:N ratio was 25–30, and the TVS content was 80–92%. The temperature of the concrete floor remained at about 27°C, but the litter temperature climbed to 38°C and averaged around 35°C, which caused considerable heat stress to the pigs.

The pigs in the sawdust litter pens became restless and somewhat aggressive. They frequented the water nipple, which they monopolized once they reached it after queuing. When they were lying on the sawdust litter, their respiration rates increased to as high as 180 breaths per minute, versus the maximum of 80 breaths per minute observed in the pigs on the concrete floor. It took 20 extra days for the pigs on the litter to reach their market weight compared with those on concrete floor, which had been hosed twice a day.

Although the first trial was not promising, additional trials were organized because of the unique advantage of the concept in Malaysia, where religious objections to pig waste meant that a system with zero liquid pollutant discharge must be used. A new barn was designed with an insulated roof and a fan cooling the pens to test the feasibility of the process in a tropical climate. In terms of operating costs, the pigs-on-litter system was as expensive as the treatment rendered by PPP.

Decanting Centrifuge

The dewatering of digester sludges with decanting centrifuges became popular in the early 1970s, particularly when aided with polymers. Several decanter models were tried and field-tested. In a test series carried out in 1982 at the Ng farm in Phase II PFA, the major factors affecting the performance of a decanting centrifuge manufactured by a German company were studied. Using sludge from an anaerobic lagoon, 123 separate centrifuge trials were conducted. In these trials, TTS of the inflow sludge varied from 3 400 to 41 800 mg/L. The cake produced varied from 15.8 to 33.1% TTS.

Feed Rate

The decanter was operated at feed rates of 0.5–5.2 m^3/h. As the feed rate increased, the liquid spent less time in the decanter; at higher rates, the solids recovery rate decreased from above 90% to less than 80%. Although there was no clear relationship between feed rate and cake dryness, the cake tended to be dryer at higher than at lower feed rates.

Bowl Speed

Three bowl speeds were evaluated (1 150, 1 825, and 2 200 rpm). The sludge was dewatered at all three speeds, but at high bowl speeds, a better quality centrate was achieved using less polymer than at lower bowl speeds. There was no relation between bowl speed, cake dryness, and machine capacity.

Differential Speed

There was a clear relation between differential speed and cake dryness. When the differential speed was increased from 3.5 to 15 at a bowl speed of 1 150 rpm, the cake solids content dropped from 20.7 to 15.7%. A similar change was observed at a bowl speed of 2 200 rpm.

Beach Length

Beach length had a less profound effect on centrate quality and cake dryness than differential speed. However, centrate quality was better with an 80-mm beach length than with a 60-mm beach length.

Polymer Concentration

Polymers flocculate the solids and make solids separation easier. A number of cationic polymers were selected for field-testing on the basis of jar tests in the laboratory. Dosages of more than 1.5 kg of polymer per tonne of TTS ceased to improve solids recovery. The optimum value for one of the polymers was found to be about 0.75 kg/t.

Digester Sludge

The decanting centrifuge installed at PPP was tested at a bowl speed of 1 762 rpm and differential speed of 12 rpm. The flow rates varied from 6 to 16 m^3/h and polyacrylamine polymers of different cationic and molecular weight were used.

Increases in the sludge feed rate increased the TSS in the centrate but improved the solids content of the cake. The centrate was recycled back into the treatment plant. The optimum sludge feed rate was 9.7 m^3/h for a maximum TTS of 19% in the cake. The characteristics of the incoming digester sludge varied from 10 100 to 63 800 mg/L. The polymer that had the highest cationic strength (50 vs 40%) and molecular weight (15×10^6 vs 3×10^6) produced a stickier cake; the other polymer produced a dryer cake. The highest suspended solids capture achieved was 95%.

Vacuum Belt Filter

A vacuum belt filter of Japanese design was used to dewater lagoon sludge. The sludge was pumped to the sludge-conditioning vessel and was thickened by adding 1 000 mg/L alum and 20 mg/L cationic polymer. The conditioned sludge was settled in a sedimentation tank before it was fed to the vacuum belt filter at about 5% TTS. An additional dose of 20–50 mg/L polymer was needed. At a feed rate of only 1 m^3/h, the vacuum filter was able to produce a cake with about 25% TTS. The filtrate was clear and free of suspended matter. The low capacity and the requirement for chemicals made this process more expensive than all the others.

Belt Filter Press

A belt filter press of British manufacture was installed at PPRTI and tested on sludge from the 15-m^3 high-rate digester. The belt filter press consisted of two horizontal continuous belts, one of which carried the sludge to be dewatered. As the belts converged, the liquid in the sludge between the belts was pressed out and the dry cake was scraped off. Actually there were three zones of dewatering: gravity, low pressure, and high pressure. The sludge was conditioned with polymers before it was fed to the belt press. The success of the belt press depended on the formation of good flocs and on the ability of the sludge to shed water. It took considerable skill and experience to establish the appropriate belt tension, belt speed, feed rate, and polymer dosing.

The polymers that had been used with the decanters and the vacuum belt were used with the belt press. The cake had a solids content of over 20% TTS. However, the polymer dosage required was 3.5–13.6 kg/t of TTS, compared with only 0.75 kg/t with the decanter. The energy requirements of the belt press were much lower than the centrifuge. Thus, the cost per pig marketed per year to dewater stabilized solids to 20% TTS was the same whether the sand filter beds, decanting centrifuge, or belt filter press was used.

Treatment of Liquids

The simplest method of liquid treatment to reduce the amount of dissolved and suspended organics is an anaerobic lagoon. The major disadvantage of anaerobic lagoons is the release of malodours. To improve solids reduction and to moderate odours, the anaerobic lagoon was modified by placing aerators on the surface. The surface aerators oxidized the hydrogen sulfide gases that were released and agitated the upper 1.5 m of the lagoon to enhance biological activity. If the aerators were designed to agitate the entire depth of the lagoon, it would become an aerated pond.

The simplest aerobic process for dilute wastewaters would be a shallow aerobic pond. But this requires a large surface area, like the algae pond described in Chapter 7, and the pig wastewaters must be diluted with clean water before they are placed in the pond.

An oxidation ditch, which is an aerobic environment, was used as an extended aeration unit under the slatted floors of pig barns at PPRTI (Chapter 8) and as an activated sludge process in the PPP (Chapter 9).

Anaerobic Lagoon

The first anaerobic lagoon was tested on the Ng farm in Phase II PFA. Based on that experience, the lagoon at PPP was developed.

Ng Farm Lagoon

The farm in the Jalan Kayu PFA had a capacity of 300 SPP. The farmer built a 3 200-m^3 concrete lagoon and installed an automatic flushing system that recirculated the lagoon supernatant under the slatted floors. The wastes from the pig houses were gravity drained into the lagoon. The lagoon was operated as an anaerobic lagoon and a solids stabilization unit.

The lagoon was not desludged. Almost 2 years later, intense gasification, prompted by several months of hot sunny weather, created large gas bubbles that carried bottom solids to the surface, mixed the lagoon contents, and replaced the pink-coloured surface layer with black liquid from the bottom. Liquid inflow moved on the surface of the lagoon to the outlet and, soon, weeds began to grow on the lagoon surface as the sludges crusted and dried. The theoretical calculation of when the lagoon would fill with solids if not desludged was 663 days (see *Solids Stabilization*, p. 308).

Initially, the performance of the lagoon was monitored without aeration. Ammonia and hydrogen sulfide emissions were monitored to compare odours from the lagoon with those from the pen floors, and with gases released when a 13.5-kW floating surface aerator was installed. During aeration, the hydrogen sulfide emission was reduced, but the ammonia concentrations remained the same. The septic odour from the lagoon changed to an inoffensive odour after aeration. When a smaller aerator (3 hp or 2.2 kW) was tried for a period of 4 weeks instead of the 10-hp (13.5-kW) aerator, hydrogen sulfide emission increased and the odour turned septic. Finally, two aerators (2.2 kW and 1.5 kW) that covered a larger surface area were tried and found satisfactory. Based on these and other tests, surface aeration design values were developed for Singapore conditions (see Chapter 9).

Lagoon effluent quality was continuously monitored from 1978 to 1981. The lagoon stabilized more than 92% of the incoming wastes as characterized by BOD_5, COD, and TTS. Aeration did not improve the performance of the lagoon in terms of waste stabilization.

The lagoon effluent was less than 300 mg/L BOD_5 and 485 mg/L TSS 50% of the time, and less than 500 mg/L BOD_5 and 650 mg/L TSS 80% of the time. Chemical coagulation of the lagoon effluent on a laboratory scale using alum and ferric chloride showed that the BOD_5 and TSS of the lagoon effluent could be reduced to less than 25 mg/L. Table 10.11 shows the additional reductions achieved using chemicals.

Modified Aerated Anaerobic Lagoon

The design parameters and rationale for the modified aerated anaerobic lagoon (AAL) were presented in Chapter 9. The modified AAL was routinely monitored from May 1985 to June 1986. Thereafter, composite samplings over a period of a week or more were carried out to determine the actual operating parameters of the lagoon.

Figure 10.3 shows the BOD_5 moving average and the data for the first 400 days of operation. Table 10.12 gives statistical ranges and frequencies of occurrence for the parameters monitored in the lagoon. The moving average of the mean BOD_5 of the lagoon effluent was 140–220 mg/L; daily data showed a range of 13–340 mg/L with a mean of 167 mg/L. This mean was exceeded about 40% of the time, as was the mean of the moving average. In other words, standards of effluent quality could be set on mean values by considering the percentage of time such values might be exceeded and thus determining whether the risk was worth taking. Such flexibility is almost prerequisite with individual feedlots. Furthermore, instead of setting effluent standard for the lagoon, it would be more practical to set standards for the size and features of the lagoon, and base the environmental risks on the type of data presented in Table 10.12.

Table 10.13 compares the performance of the lagoon with what it was designed to do. During the initial period, there were several problems with clogging of the interceptor drain and the pumping station. When the pipes were clogged, all the wastes overflowed into the lagoon. In December 1985, a pipe was installed to convey the wastewaters from Phase I barns of the industrial farm (IFPL, see Chapter 9). This added approximately 3 t of solids per day to the lagoon from a wastewater volume of 280–311 m^3/day.

Table 10.11. Chemical treatment of lagoon effluent at the Ng farm.

Trials (no.)	Flow (m^3/h)	Alum (mg/L)	Polymer (mg/L)	BOD_5 Effluent (mg/L)	BOD_5 Reduction (%)	TVS Effluent (mg/L)	TVS Reduction (%)	TSS Effluent (mg/L)	TSS Reduction (%)	COD Effluent (mg/L)	COD Reduction (%)
13	0.4–3.2	0–1700	0–2.7	35–77	3–79	140–750	0–76	230–700	0–85	115–594	13–92
7	1.6–2.6	0–440	0–13.2	96–167	4–51	360–760	34–84	90–550	36–97	217–449	42–84
12[a]	0.6–225	0–1000	0–38	21–150	42–94	240–3000	38–93	80–3750	44–99	192–2884	49–97

[a] These trials were on the lagoon contents pumped up to the pilot plant. The others were on lagoon effluent beyond the overflow weir at the lagoon outlet.

Table 10.12. Lagoon effluent characteristics.

	BOD_5 (mg/L)	COD (mg/L)	TTS (mg/L)	TSS (mg/L)	TVS (mg/L)	VSS (mg/L)	TKN (mg/L)	TAN (mg/L)	TNN (mg/L)	pH
Mean	167	759	1813	273	692	213	456	421	1	7.66
SD[a]	41%	28%	33%	68%	29%	77%	31%	37%	89%	3%
Count	164	164	166	166	164	164	161	159	152	166
Min.	13	114	650	50	68	50	128	48	0	7.08
Value equaled or exceeded										
20% of time	115	600	1400	145	540	105	305	275	0.25	7.46
50% of time	155	675	1650	190	655	175	485	435	0.80	7.67
80% of time	235	964	2200	380	860	230	580	570	1.80	7.83
Max.	340	1368	5400	1267	1250	1500	788	800	5	8.10

Note: See list of Acronyms and Abbreviations for definitions.

[a] SD, standard deviation.

Nevertheless, the lagoon was able to achieve an average effluent BOD_5 of less than 500 mg/L and a TTS concentration of 273 mg/L without sedimentation or chemical coagulation. BOD_5 removal was 90–96%.

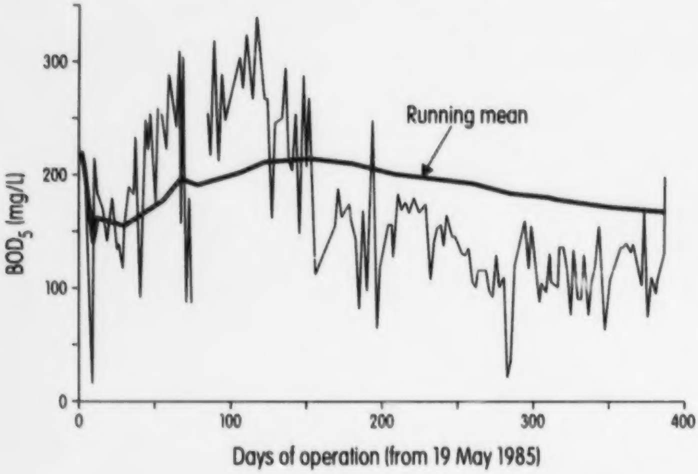


Fig. 10.3. BOD_5 moving average of PPP lagoon effluent.

Table 10.13. Design data versus actual operation data for the aerated anaerobic lagoon.

Parameter[a]	Design data	Actual data 1985–1986 (n = 93)	1987 (n = 6)	1987 (n = 6)
Wastewater volume (m^3/day)	400–650	330	467	467
Liquid volume (m^3)	25000	—	23287	—
Liquid depth (m)	5	—	4.76	—
HDT (days)	38–62	—	50	—
Inflow wastewater concentration (mg/L)				
TTS	5200	18071	6657	10372
TSS	2580	12728	4657	6872
TVS	4050	13670	4625	7236
BOD_5	2980	4803	—	4357
Loading (kg/day)				
TTS	2080	5995	3112	4843
TSS	1030	4248	2177	3209
TVS	1620	4550	2162	3379
BOD_5	1190	1539	—	2034
TVS loading (kg TVS/m^3 per day)	0.11–0.14	0.18	0.10	0.13
Solids stabilization (rates) (TVS/TTS)	0.70	—	—	0.33–0.62
BOD_5 loading (kg BOD/m^3 per day)	0.06–0.08	0.06	—	0.09
BOD_5 removal (without coagulation) (%)	50–92	96	—	91
Effluent BOD_5 (without coagulation) (mg/L)	250–1000	177	—	411

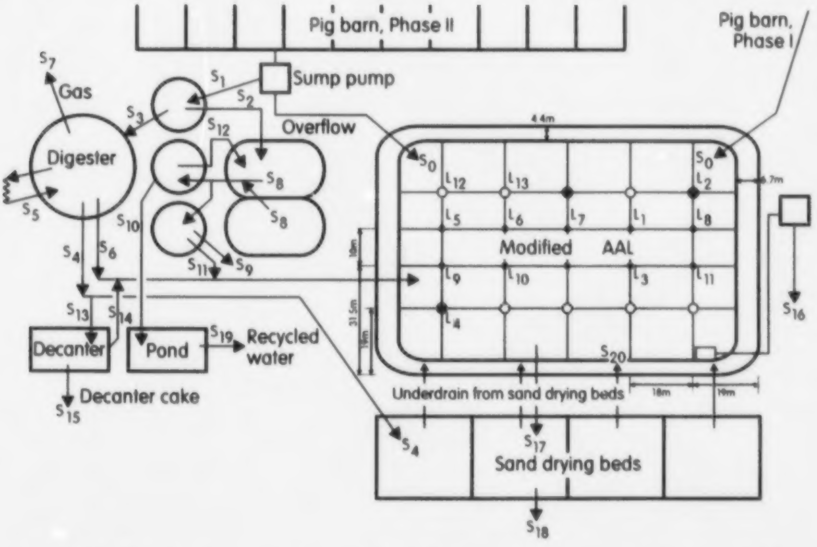
[a] See list of Acronyms and Abbreviations for definitions.

Samples were taken three times a week from May to December 1985. The other two periods of observation were 1 week each in April and May 1987; these observations were based on daily compositing of all inflows and outflows. Composite samplings were carried out at the eight lagoon inlet and outlet points shown in Fig. 10.4.

The flow rates at six of the inlets and one outlet, and the liquid level in the lagoon, were measured and composite samples were taken. The flow from the Phase I pig barns and the sump overflow were not constant. Because of tidal effects, the lagoon effluent volume was also an approximation. During the 6 days of observation, the average liquid depth in the lagoon was 4.76 m. There were no rains of any consequence during the week of sampling. Sludge was not being pumped out of the lagoon into the drying bed. The 10 aerators were operated about 10% of the time. Therefore, the data collected represent the performance of the anaerobic lagoon without aeration and without final sedimentation or coagulation. Table 10.14 gives statistical information on the metals that entered and exited the lagoon during 1 week of composite sampling.

Aerated Lagoons

An aerated lagoon is a basin that is 2–3 m deep and is oxygenated by mechanical or diffused aeration units and by induced surface aeration. The turbulence level in the basin ensures distribution of oxygen throughout the


Pig barn, Phase II
Pig barn, Phase I
Sump pump
Gas
Digester
Overflow
Decanter
Pond
Recycled water
Decanter cake
Modified AAL
Underdrain from sand drying beds
Sand drying beds
44m
6.7m
31.5m
18m
19m
S_0
S_1
S_2
S_3
S_4
S_5
S_6
S_7
S_8
S_9
S_{10}
S_{11}
S_{12}
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L_3
L_4
L_5
L_6
L_7
L_8
L_9
L_{10}
L_{11}
L_{12}
L_{13}

Fig. 10.4. Points of composite sampling of the aerated anaerobic lagoon (AAL; see Fig. 1.12): S_0, pig barn Phase I; S_{20}, dry bed filtrate; see Table 9.10 for definition of other sampling points; ○, aerators; ●, working aerators; •, moorings; L*n*, sampling stations.

Table 10.14. Metals (mg/L) entering and leaving the anaerobic lagoon.[a]

Metal	Raw waste from overflow weir (S_{11})	Raw waste from pig barn 1 (S_{10})	Digester overflow (S_5)	Digester sludge filtrate (S_6)	Lagoon effluent (S_{12})
Copper	7.3 ± 3.1 (5.3–10.9)	2.57 ± 2.81 (0.7–5.8)	3.23 ± 0.95 (2.3–4.2)	0.55 ± 0.13 (0.40–0.70)	0.74 ± 0.16 (0.50–0.85)
Iron	49.8 ± 17.7 (31.3–66.6)	22.4 ± 18.5 (11.0–43.7)	31.8 ± 4.3 (28.1–36.5)	3.2 ± 1.4 (1.7–4.8)	6.9 ± 2.3 (3.8–8.9)
Lead	0.07 ± 0.12 (ND–0.20)	0.02 ± 0.03 (ND–0.05)	0.067 ± 0.058 (ND–0.10)	0.013 ± 0.025 (ND–0.05)	0.025 ± 0.029 (ND–0.05)
Magnesium	122 ± 38 (80–153)	68 ± 48 (35–123)	99 ± 4 (95–103)	57 ± 3 (53–59)	31 ± 4 (25–34)
Phosphorus	402 ± 137 (245–495)	134 ± 75 (103–240)	260	105 ± 14 (90–118)	83 ± 11 (72.5–97.5)
Potassium	315 ± 163 (127–417)	257 ± 84 (159–364)	372 ± 75 (287–428)	312 ± 72 (262–418)	248 ± 35 (210–295)
Sodium	169 ± 12 (160–183)	113 ± 65 (61.8–186)	154 ± 17 (141–173)	105 ± 15 (88.8–123)	108 ± 9 (99–118)
Zinc	13.87 ± 6.7 (8.5–21.4)	6.1 ± 5.8 (2.5–12.8)	7.97 ± 0.55 (7.4–8.5)	0.38 ± 0.09 (0.30–0.50)	1.38 ± 0.39 (0.8–1.6)

[a] Values are means ± standard deviation with the range in parentheses. See Fig. 10.4 for location of sampling points. ND, not detected.

basin, but is usually insufficient to maintain solids in suspension. As a result, most inert solids and nonoxidized biological solids settle to the bottom and undergo anaerobic decomposition. The effluent from an aerated lagoon will have more suspended solids than effluent from an anaerobic lagoon. However, if a settling basin is included in the lagoon design, the clarified effluent will be better than the effluent from an AAL. The high energy cost for aeration makes totally aerated lagoons economically unattractive.

Oxidation Ditches

Under-Slats Oxidation Ditch

The characteristics of the mixed liquid in the oxidation ditches built under the slatted floors in two barns at PPRTI and the value of the bacteria biomass as a supplement to pig feed rations were given in Chapter 8. Table 10.15 gives statistical data from tests carried out on these ditches to determine the quality of the effluent.

Aeration tests with a "home-constructed" rotor began in July 1979. A few months later, 1.5 and 2.2 kW "Aerob-A-jets" of American manufacture were put into operation in another barn. Both treated the wastes of 90 pigs. The depth of liquid in the oxidation ditch was 1.10–1.15 m and the dissolved oxygen (DO) was 0.2–2 mg/L. The rotor was operated at speeds of 700–1 000 rpm at a depth of 10–15 cm. DO was monitored daily; if it dropped, the speed or the depth of the rotor was increased. A pH of 7.6 was maintained most of the time. The settleable solids concentration was about 400 mg/L. The hollow shaft of the rotor broke after 1 year of operation. It was replaced with a solid shaft, which performed better. A major problem with these operations was the growth of filamentous bacteria, which caused sludge bulking and created problems with the settling of flocs in the clarifier.

The mixed liquid from the ditch was pumped once a day into a 2.9-m^3 sedimentation tank for solids separation. After 2 h of settling, the sludge was spread on a sand filter bed for drying. The ditches produced an

Table 10.15. Quality of effluent from the under-slats oxidation ditch.[a]

	BOD_5 (mg/L)		TSS (mg/L)	
	Alum	No alum	Alum	No alum
Mean	10	28	30	83
Value equaled or less than				
100% of time	40	59	70	200
80% of time	14	30	50	140
50% of time	10	14	38	58
20% of time	5	10	10	25

[a] Data were collected from July 1979 to January 1981; mean values are presented. The properties of the mixed liquid and the effluent quality in 1979 were resented in Chapter 8, along with information on power consumption and other parameters.

odourless sludge that dried from 1.8% to 13% TTS in 1 day. Within 6 days, the TTS concentration increased to 19%. Alum was also used to settle the solids with excellent results (Table 10.15). The mean BOD_5 and TSS concentrations achieved with chemical treatment during final sedimentation were 10 and 32 mg/L, respectively.

PPP Oxidation Ditch

The two oxidation ditches at PPP were operated mainly as an activated sludge process with sludge recycling. The piping network and the pumping controls were such that either supernatant from the primary sedimentation tank or effluent from the anaerobic lagoon could be treated. The latter process was not attempted to any significant degree because the lagoon effluent was of better quality than expected. Another option that was not tested was intermittent operation: stopping the aerators and restarting them to promote denitrification, nitrification, and nitrogen gasification, to reduce the concentrations of nitrogen.

Table 10.16 presents data on the treatment of the effluent from the primary sedimentation tank during the first year of operation. The oxidation ditch plant was overloaded at first but the volatile suspended solids (VSS) of the mixed liquid stabilized at 400 mg/L, which was lower than the recommended range of 1 000–2 500 mg/L. The food to microorganism ratio, as represented by the ratio of BOD_5 to VSS, averaged 0.35, which is within the recommended range for conventional activated sludge plants. The oxidation ditch basins operated without any major problems. There was no excessive foaming, except when aeration was started, and the only mechanical problems were corrosion and wear and tear on the shaft of one of the rotors.

With the addition of alum, the average running means for both BOD_5 and TSS were less than 50 and 57 mg/L, respectively (Fig. 10.5). Clarification without alum was more erratic and the effluent had more than 50 mg/L of both BOD_5 and TSS. Table 10.17 gives the results of monitoring metals in the oxidation ditch basins and the clarifier.

Water Recycling

The quality of the treated water that was recycled was good, even though it was reused to flush the wastes back into the treatment plant (Table 10.18, Fig. 10.6). This means that the recycled water did not add to the waste load of the treatment plant. The quality of the recycled water was also better than the quality of water collected in surface runoff ponds on the farms. Therefore, it could be used for pig hosing.

Energy Recovery

Anaerobic digestion to stabilize solids and generate biogas energy was carried out in several tanks: 10-m^3 bags, 50-m^3 bags, a 15-m^3 high-rate

Table 10.16. Mixed liquid statistics for the oxidation basins at PPP.[a]

	BOD_5 (mg/L)	COD (mg/L)	TKN (mg/L)	TAN (mg/L)	TTS (mg/L)	TVS (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Temp. (°C)
Avg.	450	1940	233	88	3438	2020	1658	1285	6.53	27.8
SD	70%	92%	63%	59%	55%	71%	112%	109%	9%	4%
Count	106	105	101	102	106	107	107	107	107	102
Min.	90	573	63	0	700	350	100	83	5.59	26.0
Value equaled or exceeded										
20% of time	225	750	125	40	1900	950	400	400	6.02	27.0
50% of time	330	1150	170	80	2600	1300	700	600	6.32	27.8
80% of time	705	4173	400	140	6050	4100	3900	3300	7.20	28.1
Max.	1470	6566	736	240	7400	5000	6200	4600	8.01	31.0

[a] SD, standard deviation. See list of Acronyms and Abbreviations for other definitions.

Table 10.17. Metals (mg/L) in the oxidation ditch and final clarifier.[a]

Metal	Influent (S_2)	Mixed liquid suspended solids (S_7)	Effluent (S_9)	Sludge (S_8)
Copper	0.97 ± 0.73 (0.30–2.35)	1.50 ± 0.75 (0.85–3.05)	0.32 ± 0.08 (0.25–0.40)	4.3 ± 2.2 (1.30–7.30)
Iron	8.7 ± 3.9 (4.6–16.6)	21.2 ± 1.9 (18.2–23.9)	1.96 ± 1.53 (1.1–5.4)	63.7 ± 45.3 (27.3–160)
Lead	0.03 ± 0.04 (0–0.10)	0.03 ± 0.03 (0–0.05)	0.02 ± 0.06 (0–0.15)	0.10 ± 0.17 (0–0.40)
Magnesium	72 ± 19 (4.5–89)	59 ± 14 (40–76)	45 ± 17 (14–16)	75 ± 17 (53–103)
Phosphorus	174 ± 47 (108–228)	174 ± 42 (120–235)	100 ± 22 (70–118)	284 ± 88.4 (185–410)
Potassium	355 ± 105 (157–459)	267 ± 63 (183–358)	250 ± 69 (140–366)	329 ± 96 (166–412)
Sodium	116 ± 11 (96–131)	106 ± 7 (96.8–116)	106 ± 8 (94.3–121)	153 ± 25 (114–176)
Zinc	2.21 ± 1.17 (0.85–4.3)	4.41 ± 1.0 (3.05–6.0)	0.49 ± 0.12 (0.35–0.7)	13.2 ± 8.4 (5.1–29.0)

[a] Values are means ± standard deviation with the range in parentheses. See Fig 10.4 for location of sampling points.

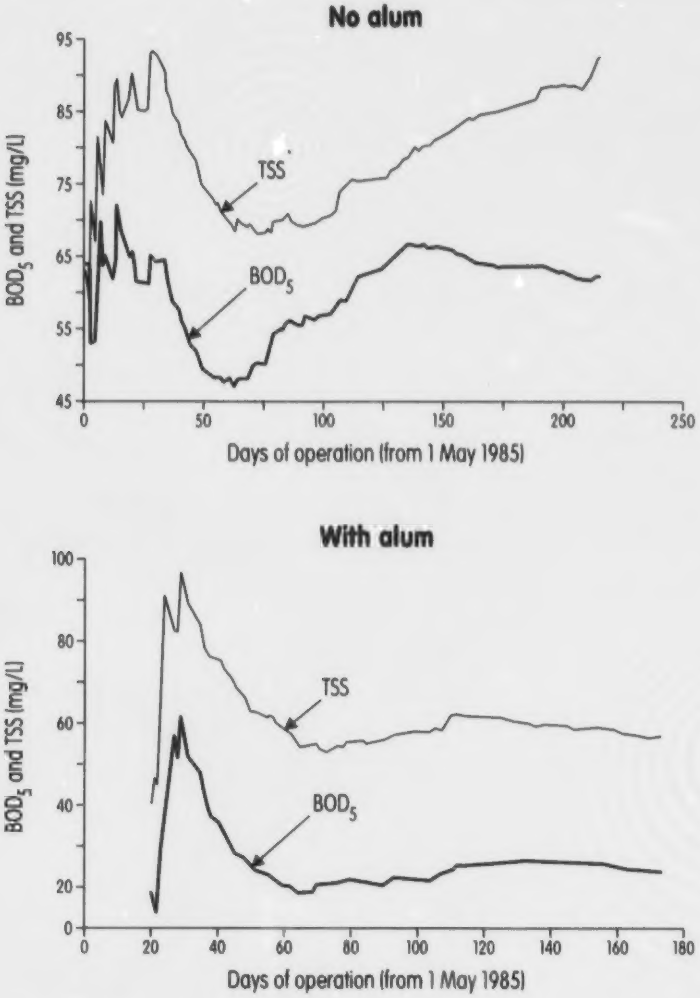

Fig. 10.5. Running means for BOD$_5$ and TSS of clarifier effluent.

digester with mechanical mixing as part of the total recycling system and the high-rate algae ponds, and a 1 500-m^3 digester as part of PPP. Data were collected under fully controlled conditions starting in June 1979 when the 15-m^3 digester was put into full operation.

Six different digester designs were proposed in sufficient detail to be assessed in terms of their technical feasibility and operating costs. One 30-m^3 thermophilic digester was installed and partially tested. Thermophilic digestion of pig wastes was not preferred over mesophilic digestion or digestion at ambient temperature, which averaged 29°C in Singapore.

Table 10.18. Characteristics of effluent water for recycling.[a]

	BOD_5 (mg/L)	COD (mg/L)	TKN (mg/L)	TAN (mg/L)	TNN (mg/L)	TTS (mg/L)	TSS (mg/L)	pH	Temp. (°C)
Mean	7	64	13	16	19	570	376	6.68	29.6
SD	80%	51%	131%	233%	117%	36%	349%	9%	4%
Count	179	180	136	163	168	181	178	181	148
Min.	1	14	0	0	0	200	3	5.18	20.0
Value equaled or exceeded									
20% of time	3	30	3	5	3	380	200	6.45	28.7
50% of time	7	59	7	10	10	570	400	6.70	29.6
80% of time	9	70	22	20	38	720	500	7.78	29.9
Max.	40	286	135	333	113	1840	10333	8.05	32.0

[a] SD, standard deviation. See list of Acronyms and Abbreviations for definitions.

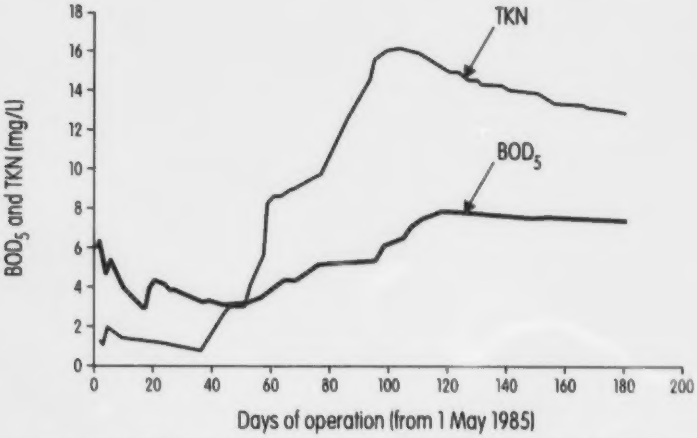

Fig. 10.6. BOD$_5$ and nitrogen content (TKN) of recycled water.

Anaerobic Digestion for Biogas Generation

If the digestion process is used to optimize gas production, then it is critical that the process parameters be maintained.

Energy Yield

In anaerobic microbial processes, air is excluded from the environment. If only one organism is used, a range of products such as lactate, ethanol, acetone, and butanol would be produced; but, in a natural population, the products are usually methane and carbon dioxide. This fermentation represents a special adaptation to a difficult environment. Without oxygen, very little energy is available for bacterial synthesis.

Most of the energy in the process is conserved in the methane (213 kcal/mol), which makes it a useful fuel to recover. This “inefficient” utilization by the microorganisms leads to another useful aspect of anaerobic digestion; biomass production is less than 0.1 kg/kg COD substrate, which saves on sludge disposal.

Microorganisms

The anaerobic process is carried out by several groups of bacteria that bring about liquefaction and hydrolysis, followed by gasification to methane and carbon dioxide. The gasification stage is rate limiting because methanogenic bacteria are slow growers. In this first stage, complex molecules, often in the solid state, are hydrolyzed to small soluble molecules. Proteins are hydrolyzed to amino acids then deaminated to organic acids. Lipids are broken down to acetic acid. Carbohydrates are hydrolyzed to simple sugars and then converted to organic acids. This stage produces the many smells of decomposing matter, mostly from protein breakdown, such as decarboxylation of amino acids to produce amines rather than organic acids.

The hydrolysis of cellulose is a special case because it is carried out by only a small group of organisms and is much faster at thermophilic temperatures. Most cellulose and ligneous solids are not broken down during digestion at short HDTs.

Other bacteria catabolize organic acids to acetic acid and hydrogen, which are utilized by methane-forming bacteria. The methanogenic bacteria are morphologically diverse. However, they have features that distinguish them from other bacteria. They have a different cell wall structure and contain coenzymes specific for methane biosynthesis.

Anaerobic digestion is a system with a high degree of interaction among diverse groups of microorganisms that influence the supply and control of essential nutrients, remove inhibitory concentrations of certain metabolites, and enhance metabolic rates through interactions among two or more species. Therefore, considerable husbandry is required to provide the nutrients, maintain a good ratio of food to microorganisms, and monitor environmental factors.

Nutrient Requirements

The carbon to nitrogen (C:N) ratio is not a good way to define the nutrient requirements because it only holds for a given set of ingredients. Even nonlignin carbon components, such as glucose and lipids, have very different rates of utilization and thus different nitrogen requirements. For digestion of animal waste solids, much of the carbon is in ligneous form and, therefore, the C:N ratio should be 15–50 to 1 to be safe. Based on the theoretical yield of biomass, a C:N ratio of 40 to 1 is adequate.

Nitrogen, in the form of ammonia, is also part of an important buffer system, and this aspect is lacking at high C:N ratios. If the pH is controlled by other means, then high C:N ratios can be used without wasting nitrogen as ammonia. Pig waste tends to have an excess of nitrogen; therefore, it can be mixed with other materials that lack nitrogen and still give good digestion. Pig waste has a high fibre content. Much of this material is present as hard, insoluble seed husks and other plant debris. This material is very resistant to microbial attack. At low HDTs, the fibrous fraction of pig waste is virtually untouched, particularly at mesophilic temperatures. Therefore, in anaerobic digestion, the rate-limiting step differs from substrate to substrate and probably also with operating conditions. Care must be exercised in setting maximum operating rates.

The phosphorus requirement is approximately one-fifth that of nitrogen. Phosphorus is adequately available in pig wastes as are potassium and essential micronutrients.

Toxicity

The common toxins of anaerobic digestion are volatile fatty acids (VFAs), ammonia, heavy metals, and disinfectants.

Acetic, propionic, and butyric acids are the fatty acids that are the intermediate by-products of digestion. If VFAs are not used by the methanogenic bacteria, fatty acids accumulate to toxic levels. VFAs exert greater toxicity at low pH (about 6.0). Pig waste digestion must be well buffered and maintained at about pH 7. Digestion ceases below pH 4.5. A VFA concentration of 3 500 mg/L is normally considered toxic.

High pH, on the other hand, induces ammonia toxicity. An increase in ammonia nitrogen to 1 500 mg/L would be toxic above pH 7.5. Up to 3 000 mg TAN/L can be tolerated after acclimatization, but gas production would be affected.

Copper, used as a pig feed additive, can affect digestion. However, adequate levels of sulfide act as an antagonist to this toxic metal. Copper is only toxic in solution in the ionic state and heavy metal sulfides have a very low solubility. Therefore, few metal ions are left in solution and the concentration is below the toxic threshold. Disinfectant chemicals, occasionally used to clean the pens, are rendered harmless by dilution and by interaction with the high organic load.

Temperature

Below 25°C, the rate of digestion falls off sharply. Between 25 and 40°C, the rates of digestion and gas production increase, but the percentage increase is variable. Between 40 and 50°C, digestion is unstable because mesophiles are at their limit and thermophiles are not working at high rates. The thermophilic range is advantageous for cellulose breakdown, but it is uneconomic for other substrates. In the mesophile range, the operating temperature depends on local conditions and the balance between increased output and the heat necessary to achieve higher operating temperatures. In Singapore, a solar panel system could be used to achieve 35–40°C most of the year. It is more important to obtain a steady operating temperature (day and night) than to attain the highest possible temperature. Although sudden temperature drops do not permanently damage the bacteria, they do result in considerable loss of activity.

Theoretical Gas Production

Gas quantity and composition are related to the chemical composition of the influent. For pure substrates, the quantity of gas and its composition can be calculated.

One mole of glucose will produce 6 moles of gas. Stoichiometrically, it can be quickly calculated that 1 kg of glucose will produce a maximum of 0.75 m^3 of gas. Therefore, maximum gas production is 0.75 m^3 gas/kg carbohydrate destroyed. Lipids can yield 1.42 m^3/kg lipid destroyed. The composition would be expected to be 71% CH_4 and 29% CO_2. The corresponding value for protein depends on how much water is considered to be involved in the reaction, but gas production will range from 0.6 to 1.05 m^3/kg protein destroyed.

With pure substrates, the highest figure obtainable is 1.44 m^3/kg volatile solids utilized. Because waste components cannot be easily quantified in terms of pure substrates, which parameter can be used to assess the gas-producing capability of the waste? The parameters normally used are BOD_5, TVS, COD, TTS, and VFA. BOD_5 will generally give a low estimate because anaerobic digestion decomposes more (and different) substrates than the bacteria in a 5-day BOD test. TVS and COD are the most commonly used design parameters by engineers, although some use TTS and VFA.

On the basis of the composition and quantities of pig waste generated on the farms in Singapore, it was projected that 0.22–0.26 m^3 gas/SPP per day would be generated if all the waste was degraded. However, the solids used in digestion are the settleable solids and do not include the easily degradable matter in the supernatant of the liquid stream. This is why some of the companies that considered demonstrating their digestion technology in Singapore recommended designs that used the entire wastewater stream.

PPRTI Digester

The 15-m^3 digester at PPRTI was seeded with anaerobic sludge pumped from one of the pig houses with under-slat detention tanks. The sludge was passed through a vibrating screen to remove hair and other fibrous material. Fresh sludge from the primary sedimentation tank was added to the anaerobic sludge to bring the volume to the operational level (15 m^3). Daily feeding of the digester involved the addition of 0.5 m^3 of fresh sludge. The intention was to start the digester at a low loading rate, with 30 days detention time, and without preheating of feed sludge or digester contents. A solar panel and heat exchanger were incorporated and used in the first series of tests only. Table 10.19 summarizes the operating variables during the start-up from 20 June to 19 December 1979. This period familiarized staff with the operation of the system.

At an organic loading rate (OLR) of 1.5 kg TVS/m^3 per day, gas production averaged 0.6 m^3/kg TVS added per day, which was comparable to productivity reported in the literature. For a high-rate digester, the expected gas production should be 0.5–1.0 m^3/kg TVS added. The initial results were lower than this expected value; the later runs at shorter HDT and higher concentration of feed solids achieved 0.45–0.54 m^3/kg TVS added. This increase in gas production per unit TVS corresponded with the commissioning of additional wastewater-collection facilities and the availability of thicker sludge for feeding the digester. The biogas was analyzed once a week and found to contain 30–33% CO_2, which indicated that digestion was proceeding normally. Although the digester was not insulated or heated the temperature remained stable (25–29°C).

A set of solar panels was used to warm the sludge for studies on heated digester performance. However, the system was not very efficient, partly because there was leakage at some points in the water pipes and partly because the water storage tank was not connected in a way that would absorb the most heat. Several attempts were made over 2 years to fix the leaks and operate the solar panel as designed, but they were futile. That part of the system was eventually abandoned. Table 10.20 shows the performance of the 15-m^3 high-rate digester over a period of 2 years.

Table 10.19. Start-up data for the 15-m^3 digester at PPRTI.

Parameter[a]	Digestion runs					
	1	2	3	4	5	6
HDT (days)	30	20	15	15	12	12
Feed volume (m^3/day)	0.5	0.75	1.0	1.0	1.25	1.25
Feed volatile solids (%)	3.3	2.0	3.4	3.1	2.5	2.5
Feed COD (g/L)	32.7	20.8	34.0	31.9	25.4	25.6
OLR						
kg TVS/m^3 per day	1.2	1.0	2.2	2.1	2.1	2.1
kg COD/m^3 per day	1.1	1.0	22.3	2.1	2.1	2.1
Gas production						
m^3/day	5.4	5.5	12.8	15.8	14.5	14.6
m^3/kg TVS added	0.26	0.39	0.36	0.54	0.45	0.50
m^3/kg COD added	0.32	0.36	0.35	0.51	0.45	0.50

[a] See list of Acronyms and Abbreviations for definitions.

Table 10.20. Performance of the PPRTI high-rate digester over 2 years.[a]

HDT (days)	Influent		OLR (kg TVS/m^3 per day)	Effluent		Gas production		
	g TVS/L	%		g TVS/L	%	m^3/m^3 digester per day	m^3/kg TVS added	m^3/kg TVS destroyed
30	22.5	80.6	0.75	—	—	0.38	0.51	—
20	19.8	80.2	0.99	—	—	0.33	0.34	—
15	30.4	81.1	2.03	18.4	80.0	1.05	0.52	1.32
12	29.1	78.9	2.43	11.5	71.4	1.05	0.43	0.71
10	25.5	83.1	2.55	16.0	78.0	1.03	0.40	1.08
10	3.1	63.3	0.31	—	—	0.11	0.36	0.22
7.5	22.0	71.4	2.94	10.3	64.4	0.75	0.26	0.49
3	1.5	56.7	0.51	—	—	0.25	0.50	0.28
3	3.2	60.1	1.06	0.8	48.8	0.27	0.25	0.18[b]

[a] Except for the 30-day HDT data, all values are averages taken over periods of operating at the indicated conditions for more than 1 month.

[b] 40% of the effluent sludge was recycled.

PPP Digester

Supernatant

The performance of the PPP digester in terms of solids stabilization and quality of inflow and outflow of sludge has been presented (see Table 10.6). Table 10.21 presents the quality of the supernatant that overflowed from the top of the digester into the anaerobic lagoon. The movement of metals in and out of the digester is shown in Table 10.22.

Biogas Composition

The methane content of the biogas started at 48%, increased to 65%, and remained at about 62% after the digester stabilized. The running mean concentrations of methane and carbon dioxide in the biogas for 120 days of operation are shown in Fig. 10.7.

Table 10.21. Quality of the digester supernatant effluent at PPP.[a]

	BOD$_5$ (mg/L)	COD (mg/L)	TKN (mg/L)	TAN (mg/L)	TTS (mg/L)	TVS (mg/L)	TSS (mg/L)	VSS (mg/L)
Mean	1389	8254	1293	845	9850	6150	7950	5602
SD	150%	91%	41%	37%	81%	96%	94%	99%
Count	150	150	144	145	150	150	150	150
Min.	150	1077	85	72	1950	450	200	50
Value equaled or exceeded								
20% of time	200	3000	1000	700	450	2250	2250	2000
50% of time	800	6000	1200	850	8000	4500	6000	3500
80% of time	1600	14000	1800	1050	15000	9250	12200	8000
Max.	17750	54378	3658	3050	54500	44500	52000	42333

[a] SD, standard deviation. See list of Acronyms and Abbreviations for definitions.

Table 10.22. Movement of metals (mg/L) through the digester at PPP.[a]

A. Sedimentation tank

Metal	Influent (S_1)	Overflow effluent (S_2)	Sludge (S_3)
Potassium	469 ± 92 (400–643)	350 ± 34 (311–437)	427 ± 49 (388–320)
Sodium	183 ± 13 (174–205)	117 ± 9 (103–128)	172 ± 17.0 (143–192)
Iron	45.6 ± 16.3 (26.2–66.5)	6.1 ± 1.0 (3.1–8.0)	49.5 ± 5.1 (42.3–56.7)
Zinc	12.8 ± 5.3 (7.4–19.6)	1.97 ± 0.34 (1.6–2.6)	13.5 ± 1.2 (11.9–15.1)
Magnesium	181 ± 48 (110–230)	84.5 ± 8.8 (75–99)	135.5 ± 17.1 (133–175)
Copper	6.2 ± 3.9 (2.5–13.2)	1.13 ± 0.33 (0.8–1.6)	6.8 ± 2.2 (4.4–10.6)
Lead	0.36 ± 0.17 (0.15–0.60)	0.09 ± 0.10 (0–0.25)	0.36 ± 0.21 (0.10–0.60)
Phosphorus	560 ± 131 (328–695)	185 ± 86 (132–350)	363 ± 179 (455–925)

B. Biogas digester

Metal	Influent (S_3)	Overflow effluent (S_5)	Sludge (S_4)
Potassium	403 ± 27 (372–432)	460 ± 42 (418–318)	457 ± 51 (393–524)
Sodium	159 ± 9 (144–165)	178 ± 7 (173–189)	177 ± 7 (171–189)
Iron	67.3 ± 66.3 (24.5–185)	32 ± 9.5 (41.5–62.8)	62.3 ± 22.1 (26.5–87.5)
Zinc	12.6 ± 12.4 (3.2–34.6)	12.7 ± 1.8 (9.7–14.5)	15.6 ± 4.0 (5.9–21.2)
Magnesium	110 ± 40 (68–213)	135 ± 16 (115–153)	157 ± 32 (110–195)
Copper	7.9 ± 10.7 (0.8–26.7)	4.8 ± 1.7 (2.9–7.0)	7 ± 3.6 (2.6–11.1)
Lead	0.14 ± 0.11 (0–0.30)	0.12 ± 0.22 (0–0.30)	0.12 ± 0.22 (0–0.30)
Phosphorus	468 ± 278 (235–783)	468 ± 168 (330–750)	396 ± 284 (310–1043)

[a] Values are means ± standard deviation with the range in parentheses. See Fig. 10.4 for location of sampling points.

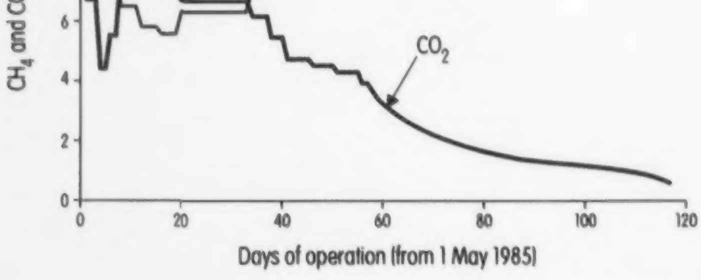

Fig. 10.7. Methane (CH_4) and carbon dioxide (CO_2) content of biogas.

Table 10.23. Composition and production of biogas by the PPP digester.

	CH_4 (%)	CO_2 (%)	H_2 (%)	CO (%)	O_2 (%)	N_2 (%)	Production (m^3/day)
Mean	58	33	4	0.181	0.200	3.5	621
SD[a]	9%	15%	45%	64%	44%	45%	48%
Count	73	73	73	73	73	72	46
Min.	36	22	2	0.000	0.000	0.2	83
Value equaled or exceeded							
20% of time	58.0	30.5	2.6	0.000	0.165	2.0	365
50% of time	59.0	33.0	3.9	0.185	0.180	3.7	580
80% of time	62.5	34.5	5.2	0.198	0.195	4.5	965
Max.	65	55	12	0.400	0.600	11.4	1182

[a] SD, standard deviation.

Whether the digester was heated or run at ambient temperature, the composition of the gas remained the same. Table 10.23 gives the composition and production averages for the first 120 days of operation. Methane content was about 63% whether the digester was heated to 35°C or not; however, gas production was affected.

Biogas Production

Figure 10.8 shows that gas production reached a maximum of only 1 182 m^3/day, which was less than the design amount. One reason for not achieving the design production was the drop in fresh wastes coming into the digester. The OLR of the digester was 0.8–1.16 kg TVS/m^3 per day, which was much below the design value of 2.9 kg TVS/m^3 per day. This was because the pig population contributing to the plant did not reach its projected level and because some of the wastes were diverted. During a controlled experiment, the digester produced 15% more gas when it was heated than when it was not.

Figure 10.9 shows that the hourly rate of production was highly variable. Gas generation started immediately after the digester was loaded between 0900 and 1000 and began to decline when the pumping of sludge into the digester ceased about 1600. This variability affected the utilization of the gas for the electricity generator.

Biogas Utilization

The generated gas was used directly without pressure storage. The only pressure was produced by the floating cover, and this decreased as the gas was used. The gas was used to fire a boiler to heat the recirculating sludge and was burned in a waste gas burner when not used for the generator. The gas generator was of American manufacture and was rated at 88 kVA (70 kW at a 0.8 power factor). The gas engine was fed with biogas coming directly from the digester. The pipeline pressure was 3.0–3.6 kPa, but the optimum pressure for the gas engine was 20–140 kPa. The low gas line pressure made it difficult to meter the correct amount of gas into the engine and resulted in excessively lean fuel mixtures. Although the gas engine

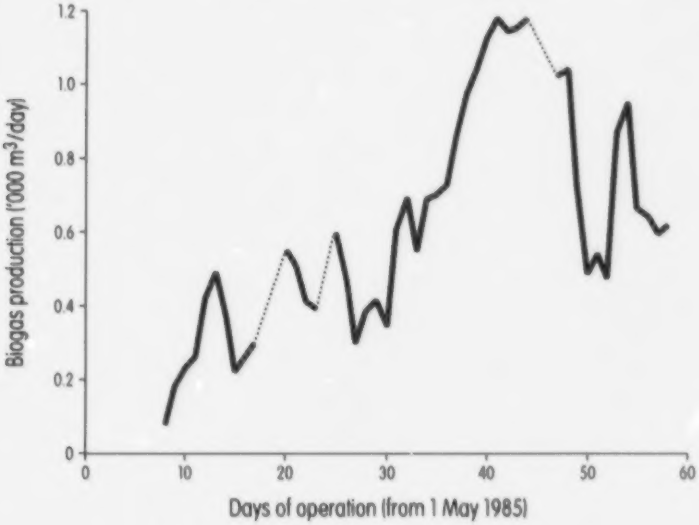

Fig. 10.8. Biogas production of the PPP digester.

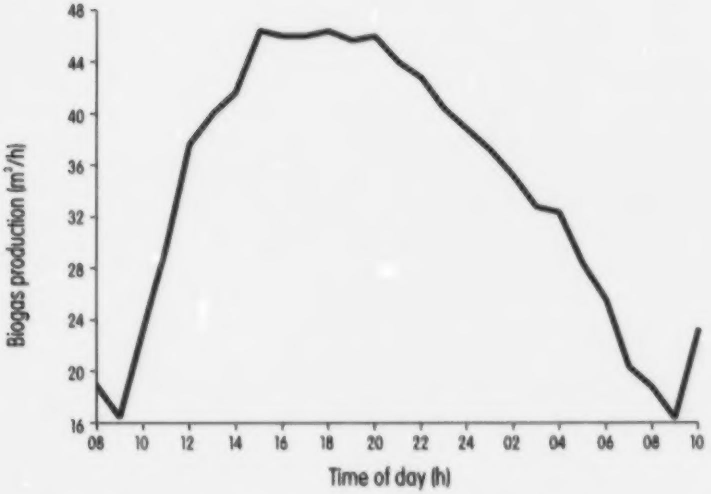

Fig. 10.9. Hourly rate of biogas generation by the PPP digester.

was equipped with two carburetors to compensate for the low gas pressure, the performance efficiency was low.

From analyses of the engine exhaust gases, which were high in oxygen, it was determined that the engine was running on a dilute fuel–air mixture. The average air to fuel ratio was 1.807 kmol air/kmol biogas (2.061 kg air/kg biogas); stoichiometrically, the correct air to fuel ratio was 2.311 kmol air/kmol biogas. The gas engine was running at about 38% excess air. Because of this and the low flame-propagation speed of the biogas, the best efficiency attained by the generator was about 11%; it was designed for an efficiency of 20%.

Acronyms and Abbreviations

AAL	aerated anaerobic lagoon
ADAB	Australian Development Assistance Bureau (Canberra, Australia)
ALW	animal live weight
AOC	annual operating costs
APU	animal production unit
ASEAN	Association of South East Asian Nations (Jakarta, Indonesia)
BDT	best demonstrated treatment
BOD	biochemical oxygen demand
BOD_5	biochemical oxygen demand after 5 days
BV	biological value
CFU	colony-forming unit
CGS	Capital Grants Scheme
COD	chemical oxygen demand
CODR	reduction in chemical oxygen demand
CP	crude protein
DAF	dissolved air flotation
DC	digestibility coefficient
DFS	dissolved fixed solids
DO	dissolved oxygen
EIS	environmental impact assessment statement

FAO	Food and Agriculture Organization of the United Nations (Rome, Italy)
FP	fermented product
GBP	gross biomass productivity
GTZ	German Agency for Technical Cooperation (Eschborn, Germany)
HDT	hydraulic detention time
ICC	initial capital costs
IDRC	International Development Research Centre (Ottawa, Canada)
IFPL	Industrial Farm Pte Ltd (Singapore)
MARDI	Malaysian Agricultural Research and Development Institute (Kuala Lumpur, Malaysia)
MET	most economical treatment
MIG	malodour index gas
MPT	most practical treatment
MWT	modular waste treatment
NPU	net protein utilization
NR	nitrogen reduction
OLR	organic loading rate
PER	protein efficiency ratio
PFA	pig feedlot farming area
PH	person-hour
PMY	porkers marketed per year
PPC	Ponggol Pig Centre (Singapore)
PPD	Primary Production Department (Ministry of National Development, Republic of Singapore)
PPP	Ponggol Pigwaste Plant (Singapore)
PPRTI	Pig and Poultry Research and Training Institute (Singapore)
R&D	research and development
SCP	single-cell protein
SFR	solids flux rate
SFS	suspended fixed solids
SLS	settleable solids

SOS	sulfate sulfur
SPM	standing pig marketed
SPP	standing pig population
SRT	solids retention time
SSP	standing sow population
SST	solids stabilization treatment
STT	stabilized treatment technology
TAN	total ammonia nitrogen
TCDC	Technical Cooperation among Developing Countries
TDS	total dissolved solids (or nonfilterable solids)
TFS	total fixed solids (or inorganic solids)
TKK	total potassium
TKN	total Kjeldahl nitrogen
TKO	total potash
TLW	total live weight
TNA	total nitrates
TNN	total nitrate nitrogen
TPO	total phosphates
TPP	total phosphorus
TSS	total suspended solids (or filterable residue)
TTS	total solids
TVS	total volatile solids (or organic solids)
TWF	total waste flow
TWW	total wet weight
UNDP	United Nations Development Programme (New York, USA)
USD	United States dollar
VFA	volatile fatty acid
VSS	volatile suspended solids
WWS	wastewatershed

Sources

This bibliography lists, by chapter, all of the source material that was used in the preparation of this book. Many of the sources were used in more than one chapter and, therefore, appear more than once in this list. All original sources are maintained at the Library of the Pig and Poultry Research and Training Institute, Sembawang Field Experiment Station, Primary Production Department, 17 Km Sembawang Road, Singapore 2776, Republic of Singapore.

Chapter 1

ARC/NUS (Applied Research Corporation, National University of Singapore). 1989. Proceedings of the International Symposium on Waste Management and Recycling in Pig Farms, Singapore, 9–10 October 1989. National University of Singapore, Republic of Singapore. 200 pp.

Barcelon, E.G. 1987. Performance of a 15 m^3 anaerobic digester using raw dilute wastes. 27 pp.

Choo, P.Y., Taiganides, E.P., ed. 1988. Pig farming in Malaysia: 1988 workshop proceedings. Animal Waste Management and Pollution Control, Department of Veterinary Services, Ministry of Agriculture, Kuala Lumpur, Malaysia. UNDP/FAO-MAL/84/001, 200 pp.

Chou, K. C. 1978. Animal production in Argentina and USA. 7 pp.

Dodd, J.C. 1978. Preliminary conceptual plan for treatment and disposal of pig wastewater draining to Sungai Punggol. 12 pp.

____ 1979. Comprehensive plan for the Ponggol pig estates. 100 pp.

Dodd, J.C., Ravishanker, P. 1979. Wastewater treatment alternatives for intensive pig farming estates. 9 pp.

Edi, I.W. 1987. Effect of mixing time on biogas production. 20 pp.

FAO (Food and Agriculture Organization of the United Nations). 1985. Animal waste management and utilization: Singapore. Project findings and recommendations. Terminal Report. FAO, Rome Italy. AG: DP/SIN/74/006. 26 pp.

Forster, D.L. 1979. A framework for economic analysis of pig wastes. 37 pp.

Goh, A C. 1981. Results of tests on chemical treatment of pig wastewaters using the EDEX system. 65 pp.

Goh, A.C., Lee, B.Y. 1983. Piggery waste treatment by high-rate algae ponds: Phase II Completion Report. 200 pp.

Hols, H. 1984. Evaluation of the PPRTI digester performance 1979–1981. 12 pp.

____ 1984. Total recycle of the PPRTI plant. 12 pp.

Jung, D.I. 1987. Performance of the 15 cubic metre anaerobic digester using diluted raw pigwaste with recycle. 14 pp.

Lee, B.Y., Low, C.F., Ravishanker, P., Yao, C.L. 1979. Pig waste treatment in Japan. 130 pp.

Low, C.F. 1988. Development and administration of Ponggol Phase II PFA. 25 pp.

Poon, C.T. 1979. Biogas energy from anaerobic fermentation. 66 pp.

PPD (Primary Production Department). 1982. Guidelines for the planning and construction of pig farm waste treatment systems. PPD, Ministry of National Development, Republic of Singapore. 36 pp.

Seo, Y.C. 1987. Performance of a 1500 m^3 anaerobic digester using pigwaste in Ponggol, Singapore. 20 pp.

Siew, T.W., Ngiam, T.T., Taiganides, E.P. 1979. Briefing of MND Minister, Teh Cheang Wan, and aides. 20 pp.

Silverio, C.M. 1987. Performance of a 15 m^3 biogas digester at different hydraulic detention times. 31 pp.

Sim, T.S., Taiganides, E.P. 1980. Biological treatment of wastewaters. *In* Proceedings of a workshop on Microbiology and Human Welfare in Singapore, 14–15 November 1980. Singapore Society of Microbiology, Republic of Singapore. pp 61–68.

Taiganides, E.P. 1976. Calculations to estimate cost of pig waste treatment for Singapore pig estates. 16 pp.

____ 1978. Travel report to Kuala Lumpur: rotary screen inspection. 2 pp.

____ 1979. Biogas — Energy recovery from animal wastes: background information. 45 pp.

____ 1979. Central treatment plants: factors. 20 pp.

____ 1980. Central treatment plant for WWS 19 — proposal for a demonstration plant. 30 pp.

____ 1980. Rebates schemes for the rapid construction of wastewater treatment plants. 30 pp.

____ 1982. Rebates: implementation costs. 22 pp.

Taiganides, E.P., Bhattarai, K.K., Yap, B.C., Lee, K.W. 1988. Training engineers with hands-on research mini-projects. *In* Proceedings of the First World Congress on Engineering and Education Training, 13–15 November 1988. University of Nepal, Kathmandu, Nepal.

Taiganides, E.P., Choo, P.Y., Yap, T.C., ed. 1987. Pig farming in Malaysia. Proceedings of a workshop on pig farming, 7–9 January 1987, Port Dickson, N. Sembilon, Malaysia. Animal Waste Management and Pollution Control, Department of Veterinary Services, Ministry of Agriculture, Kuala Lumpur, Malaysia. UNDP/FAO-MAL/84/001, 128 pp.

Taiganides, E.P., Ho, Y.K., Ngiam, T.T. 1977. Waste disposal, disease control, and production management at pig feedlots in Europe. 38 pp.

Taiganides, E.P., Hols, H. 1984. Design and performance of biogas plants. *In* Proceedings of the ASEAN Workshop on Biogas Technology, 9–13 October 1984, K Trengannu, Malaysia. Ministry of Science, Tecnology, and Environment, Kuala Lumpur, Malaysia. pp. 256–267.

Taiganides, E.P., Lee, B.Y., Chou, K.C. 1979. Animal waste management in Singapore. Agricultural Wastes, 1(2), 129–141.

Taiganides, E.P., Mensch, R.L., Ngiam, T.T. 1982. Pig waste management seminar/exhibition. 30 pp.

Taiganides, E.P., Ngiam, T.T., Yap, B.C. 1982. Waste treatment technologies in Australia. 38 pp.

Taiganides, E.P., Ravishanker, P. 1979. Pilot treatment plant for pig wastewatershed No. 19: alternative designs and costs. 60 pp.

Thaveesak N. 1987. Performance of a 15 cubic metre digester using raw pigwaste with sludge recycle. 33 pp.

Thiruchelvam, S. 1979. Pig and poultry production and waste recycle in Japan. 18 pp.

Yap, B.C. 1988. Research and training in waste resource recovery biotechnologies and pollution control. Completion Report. 70 pp.

Chapter 2

Choo, P.Y. 1986. Management of intensive PFA. 70 pp.

Mensch, R.L. 1984. Pig farm engineering. Termination Report. 36 pp.

Miner, J.R. 1981. Computer program to store and process pig breeding data. 10 pp.

Ong, H.K. 1986. Feeds and feeding practices in Singapore. 100 pp.

Taiganides, E.P. 1976. Report of duty travel to Malaysia: pig farming practices. 3 pp.

Taiganides, E.P., Ho, Y.K., Ngiam, T.T. 1977. Waste disposal, disease control, and production management at pig feedlots in Europe. 38 pp.

Tan, S.L. 1986. Epidemiology of pig diseases in intensive PFA. 35 pp.

Chapter 3

Esmay, M. 1981. Animal housing ventilation for the hot climatic conditions in Singapore. 49 pp.

Khoo, K.H. 1986. Evaluation of the housing arrangements and construction of pig farms in the Ponggol PFA. 70 pp.

Parker, G.B. 1980. Improving the design and construction of pig farm structures. 60 pp.

Chapter 4

Lee, B.Y., Low, C.F., Ravishanker, P., Yao, C.L. 1979. Pig waste treatment in Japan. 130 pp.

Loh, S.H. 1986. Cost of pig housing facilities for a 200-sow and 600-sow model pig farm. 89 pp.

Mensch, R.L. 1979. Handbook for layout of pig farms with flushing systems. 30 pp.

____ 1979. Critique of model farm plans. 10 pp.

____ 1984. Singapore pig farm design handbook. 297 pp.

Mensch, R.L., Chin, H.K. 1981. ASEAN barn plans. 5 pp.

Soh, K.H. 1986. Unit costs of pig housing facilities. 44 pp.

Willie, J.L. 1980. Improving the design and construction of chicken and duck farm structures. 65 pp.

Chapter 5

ASAE (American Society of Agricultural Engineers). 1983. Manure production and characteristics. ASAE, St Joseph, MI, USA. Agricultural Engineers Yearbook of Statistics D384.

Dodd, J.C. 1978. Treatment and disposal of pig wastewaters in the Ponggol River Estuary: conceptual and interim plans. 18 pp.

Goh, A.C. 1980. Potability of lagoon effluent. 15 pp.

Khoo, T.H., Taiganides, E.P. 1976. Pig waste stabilization rates. 4 pp.

Mensch, R.L. 1978. Cesspit performance and management studies. 58 pp.

Miner, J.R. 1981. System to collect lagoon sludge and/or lagoon effluent and transport it to tidal ponds for polishing treatment. 15 pp.

____ 1981. An assessment of the water quality impact of pig farming on the Ponggol River, Serangoon River and potential beach sites along the Straits of Johore. 21 pp.

Mohajit, Bhattarai, K.K., Taiganides, E.P., Yap, B.C. 1989. Struvite deposits in pipes and aerators. Biological Wastes, 30, 133–147.

Ngian, M.F., Mensch, R.L. 1978. Report on the daily variations [of constituent concentrations] in cesspit effluents. 17 pp.

Puspa, D.N.L. 1986. Standards methods of laboratory tests for waste parameters and removal efficiencies in chemically aided clarifiers. 48 pp.

Rachadawan, P.-A. 1987. Bacteriological analyses of pig wastewater recycle system at Sembawang, Singapore. 52 pp.

Taiganides, E.P. 1977. Report of duty travel to USA and Rome: sampling equipment. 7 pp.

____ 1977. Bioengineering properties of feedlot wastes. *In* Taiganides, E.P., ed., Animal wastes. Elsevier Publishing Co. Ltd, London, UK. 135 pp.

Teo, S.S., Taiganides, E.P., Yap, T.C. 1988. Engineering design parameters of wastes from pig farms in Malaysia. Biological Wastes, 24, 95–104.

Chapter 6

Miner, J.R. 1978. Investigations on production of malodours at the Jalan Kayu pig estate. 37 pp.

Ngian, M.F., Scammel, G.W., Nah, K.C. 1980. The influence of dietary fibre and zeolite intake on the composition and odour of pig feces. 6 pp.

Ravishanker, P. 1978. Odour studies at Jalan Kayu lagoon. 15 pp.

Scammel, G.W. 1979. Malodour studies and surveys in the Jalan Kayu pig estate. 66 pp.

Taiganides, E.P. 1978. Olfaction and malodour: principles and factors to consider. 12 pp.

Chapter 7

Becker, E.W. 1979. Microbiology and evaluation of HRAP system. 99 pp.

Buelna, G. 1987. Evaluation of various flocculants for the recovery of algae biomass on pigwaste. 20 pp.

Buelna, G., Bhattarai, K.K., de la Noue, J., Taiganides, E.P. 1990. Evaluation of various flocculants for the recovery of algae biomass grown on pig-waste. Biological Wastes, 31, 211–222.

Dodd, J.C. 1978. Production and use of micro-algae biomass. 9 pp.

Dongjai, K. 1987. The effectiveness of photozone in removing algae and bacteria from algae wastewaters. 55 pp.

Goh, A.C., Lee, B.Y. 1983. Piggery waste treatment by high-rate algae ponds: Phase II Completion Report. 200 pp.

IDRC (International Development Research Centre). 1980. Wastewater treatment and resource recovery. Report of a workshop on high-rate algae ponds, Singapore, 27–29 February 1980. IDRC, Ottawa, Ont., Canada. IDRC-154e, 47 pp.

Kempis, E.P. 1987. Concentration of heavy metals in the pig waste treatment plant at Ponggol. 22 pp.

Kossila, V. 1982. Design of feeding wastes to pigs. 40 pp.

Lee, B.Y. 1979. The utilization of pig wastewater for algal protein recovery in high-rate ponds. 8 pp.

Lee, B.Y., Dodd, J.C. 1979. Pig wastewater treatment and nutrient recovery by high rate algae ponds. Phase I Completion Report. 44 pp.

Lee, B.Y., Yap, J. 1979. Report on pre-project tour to Israel, West Germany, and Thailand. 17 pp.

Managaban, L.M. 1987. Effect of pH on algal dominance. 15 pp.

____ 1987. Toxicity evaluation of waste-grown algae. 23 pp.

Narumon, S. 1986. Treatment of dilute pig wastewater using high-rate algae ponds: effect of hydraulic detention time. 30 pp.

Ngian, M.F. 1978. Studies on the utilization of piggery wastes. 14 pp.

Pornthip, P. 1987. Heavy metal concentrations in the high rate algae total recycle system at Sembawang, Singapore. 64 pp.

Roongnapa, K. 1987. Effect of varied organic loading rates of pig waste on *Moina* sp. production in high-rate algae ponds. 37 pp.

Sandbank, R., Poon, C.T. 1980. Design of an experimental dissolved air flotation algae harvester. 12 pp.

Sawitri, C. 1986. Concentrating algae slurries using the DAF and the centrifuge. 38 pp.

Somchai, C. 1987. Utilization of dried sludge and algae effluent by weaner pigs. 30 pp.

Supajjunya, N., Bhattarai, K.K., Taiganides, E.P. 1987. Effect of hydraulic detention time on treatment of dilute pig wastewaters using high-rate algae ponds. Singapore Journal of Primary Industries, 15(1), 23–29.

Taiganides, E.P. 1976. Report of duty travel to Thailand: algae research at Kasetsart University. 11 pp.

____ 1977. Report of duty travel to Gi-Gi in Italy: aeration and SCP fermentations. 3 pp.

Tan, B.T. 1981. Feasibility study of the high-rate algae pond treatment system for piggery waste. 55 pp.

Chapter 8

Ngian, M.F. 1979. Solid fermentation of piggery wastes using Rebreath as inoculum. 7 pp.

Ngian, M.F., Thiruchelvam, S. 1979. A nutritional evaluation of oxidation ditch mixed liquor. 10 pp.

____ 1979. A nutritional evaluation of dried pig feces. 10 pp.

Ravishanker, P. 1981. On-farm under-slat aeration. Pig and Poultry Research and Training Institute, Primary Production Department, Ministry of National Development, Republic of Singapore. PPRTI Annual Report. 8 pp.

Scammel, G.W. 1978. Intermediate report on fungi fermentation studies. 66 pp.

____ 1980. Final report and recommendations. 28 pp.

Sim, T.S. 1980. Mycotoxins in animal wastes and feeds. 50 pp.

Thambirajah, J.J. 1980. Solid-state surface fermentation of pig faeces supplemented with carbohydrate sources. Singapore Journal of Primary Industries, 8(1), 1–8.

Chapter 9

Cornell, M. 1983. Unit costs of construction bids for PPP. 200 pp.

Cornell, M., Anderson, J.L. 1983. Specifications for sedimentation tanks. 42 pp.

____ 1983. Construction drawings for Phase 2. 170 pp.

____ 1983. Specifications for oxidation ditch. 48 pp.

____ 1983. Specifications for anaerobic digester. 48 pp.

____ 1983. Construction design report for PPP. 182 pp.

____ 1983. Specifications for progressive cavity pumps. 38 pp.

____ 1983. Specifications for chemical dosing equipment. 40 pp.

____ 1983. Specifications for decanter. 38 pp.

Cornell, M., Anderson, J.L., Seward, G.S. 1983. PPP — Preliminary report for Phase 2 contract. 80 pp.

Cornell, M., Derrick, B.F. 1983. PPP — Preliminary report for Phase 1 contract. 65 pp.

____ 1983. Construction drawings for Phase 1. 44 pp.

Georgaiadis, A., Cornell, M. 1983. Engineering consultant contract. 66 pp.

Mensch, R L. 1979. On-farm waste management: Termination Report. 25 pp.

Millis, D. 1983. Calculations for the structural components of the PPP. 75 pp.

Rannfelt, C., Doeve, A., Taiganides, E.P. 1982. Briefing report for consultants on the pigwaste treatment and utilization demonstration project. 10 pp.

Ravishanker, P. 1979. Wastewater treatment and utilization: study tour to USA. 49 pp.

Taiganides, E.P. 1982. Preliminary systems report for the Ponggol Pigwaste plant. 28 pp.

Taiganides, E.P., Ngiam, T.T., Yap, B.C. 1982. Waste treatment technologies in Australia. 38 pp.

Chapter 10

Agustine, L. 1987. Concentration of heavy metals in the pigwaste treatment plant at Ponggol, Singapore. 25 pp.

Barcelon, E. 1987. Sludge drying in open sand filter beds at different solid flux rates. 50 pp.

Bharata, K. 1987. Sludge drying and mechanical harvesting on sand beds. 43 pp.

FAO (Food and Agriculture Organization of the United Nations). 1985. Pig waste treatment and utilization demonstration project: Singapore. Project findings and recommendations. Terminal Report. Government Cooperative Programme, FAO, Rome, Italy. FAO/GCP/SIN/001/AUL. 31 pp.

Goh, A.C., Woon, C.C. 1981. On-farm waste treatment system — an economic analysis of the lagoon system. 55 pp.

____ 1982. Dewatering of storage pit sludge. 75 pp.

Griansak, C. 1987. Composting of dried lagoon sludge in open windrow piles. 25 pp.

Hols, H. 1983. Pig waste treatment with nitrification–denitrification. 30 pp.

____ 1983. Solids dewatering with filter belt press. 17 pp.

Idryati, V. 1987. Performance of a 1500 m^3 digester in Ponggol, Singapore. 14 pp.

Inswiasri, S. 1987. Drying of sludge in open sand-drying beds. 35 pp.

Liliansari, L. 1987. Composting process of dried digested sludge in open windrow piles. 14 pp.

Mensch, R.L. 1979. Handling solids wastes from cesspits. 63 pp.

____ 1982. Seminar on flushing systems. 30 pp.

Mensch, R.L., Miner, J.R., Taiganides, E.P., Chin, H.K. 1980. Engineering drawings for Farm CF92. 4 pp.

Miner, J.R. 1981. Proposed integrated waste collection and treatment scheme to serve the commercial farms in Ponggol Phase I. 5 pp.

____ 1981. Handling of sludge from anaerobic lagoons. 83 pp.

____ 1981. Background materials for the selection of methods of pig wastewater treatment and solids handling. 27 pp.

____ 1981. Allocating the cost of pig farm wastewater treatment. 12 pp.

Miner, J.R., Goh, A., Taiganides, E.P. 1983. Chemical treatment of anaerobic swine manure lagoon effluent and contents. Transactions of the American Society of Agricultural Engineers (ASAE), 26(4), 1177–1180.

Mohajit. 1986. Struvite crystallization in pipes and aerators: growth and removal. 38 pp.

____ 1987. Struvite crystallization in piles and aerators: formulation. 40 pp.

Panaligan, C.A. 1986. Operation of biogas digesters and sedimentation tank at low hydraulic detention times and different overflow rates respectively of pig wastewaters. 163 pp.

Paran, A.P. 1987. Performance of a Caterpillar 3306 natural gas engine running on biogas. 62 pp.

Ploenpit, V.-a. 1987. Sludge dewatering by dewatering centrifuge using polymers. 22 pp.

Preeda, Y. 1987. Solids loading and performance of the modified anaerobic lagoon in Ponggol. 23 pp.

Ramirez, A.M. 1986. Biogas production with and without sludge heating in 1500 m^3 anaerobic digester. 128 pp.

Ramirez, A.M., Bhattarai, K.K., Taiganides, E.P. 1987. Biogas production with and without sludge heating in a 1500 cubic meter anaerobic digester. Singapore Journal of Primary Industries, 15(2), 129–138.

Ravishanker, P. 1983. Analysis on unit processes and operations in pig waste treatment and technologies. 180 pp.

Rayos, L.V. 1986. A case study of construction management for pig waste treatment plant in Singapore. 64 pp.

Saimorn, L. 1987. Sludge composting in open windrow piles: predominance of fungi and affect of sludge age and inoculum. 20 pp.

Siah, C.S. 1986. Unit costs of pigwaste treatment facilities. 29 pp.

Sittiporn, K. 1987. Dewatering of digester sludge using a decanter centrifuge. 26 pp.

Suazo, R.B. 1987. Sludge accumulation in the modified anaerobic lagoon. 29 pp.

Taiganides, E.P. 1980. Biogas — Energy recovery from animal wastes. Part I. FAO World Animal Review, 35, 2–15.

____ 1980. Biogas — Energy recovery from animal wastes. Part II. FAO World Animal Review, 36, 15–24.

____ 1986. Animal farming effluent problems — an integrated approach: resource recovery in large scale pig farming. Water Science and Technology, 18, 47–55.

Teoh, S.S. 1986. Engineering unit costs for materials, equipment, and unit facilities in treatment plants. 72 pp.

Woon, C,C., Ong, K.S. 1985. Decanter and gas engine generator operation data for 1985 at the PPP. 10 pp.

Woon, C.C., Ong, K.S., Lim, K.C., Chin, H.K. 1986. Operational data for the 19 sampling points of the Ponggol Pigwaste Plant (PPP) from 2 May 1985 to 31 March 1986. 100 pp.

Yap, B.C. 1988. Design, operation, and performance of the aerated anaerobic lagoon in the PPP. 17 pp.

Yutiamco, A.P. 1987. Efficiencies in the conversion of biogas to electricity. 20 pp.

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The Singapore Experience

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